Hybrid Drive Systems for Vehicles

- L5
  - Alternative drive train Components

Drawback with conventional drivetrains

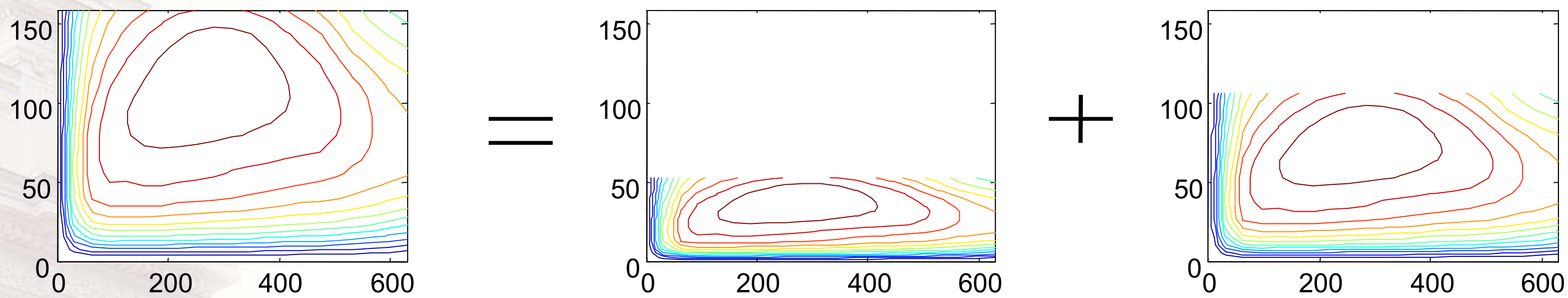
- Limited ability to optimize operating point

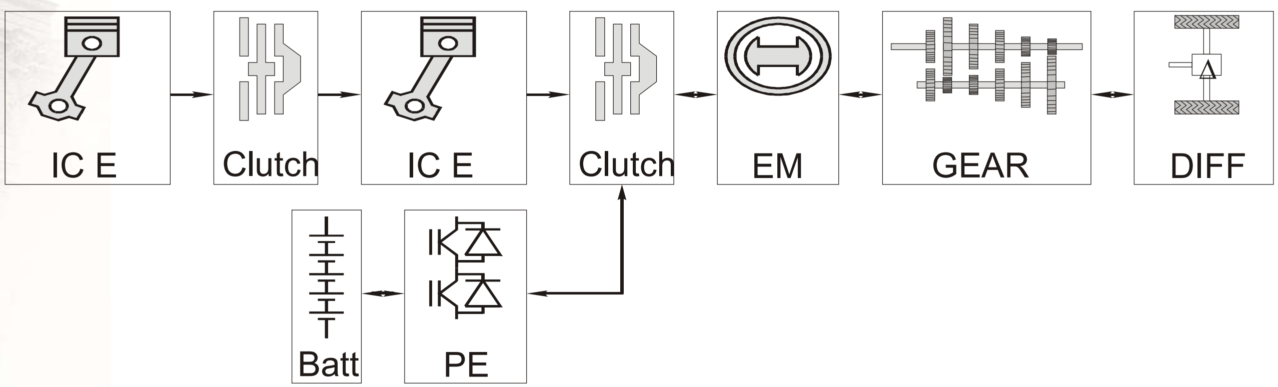
- No ability to regenerate braking power

Solutions

- Smaller Engine
  + Reach higher operating points
  - Still cannot regenerate
- Store energy in the vehicle mass
  - Speed variations
  - Still cannot regenerate
- Secondary energy storage
  + Selectable operating point (Pstorage = Pice – Proad)
  + Can regererate
  - Expensive

Smaller Engine – cylinder deactivation



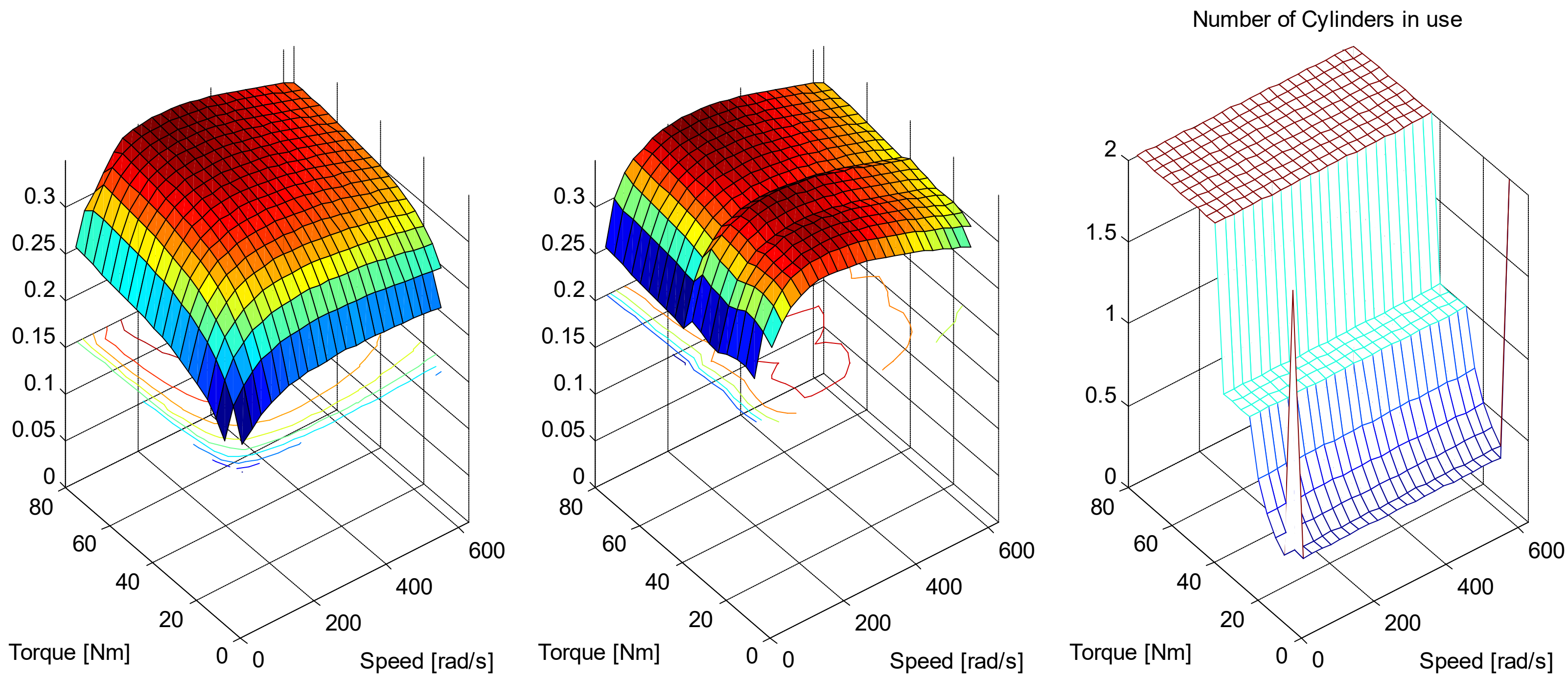


Combustion On Demand

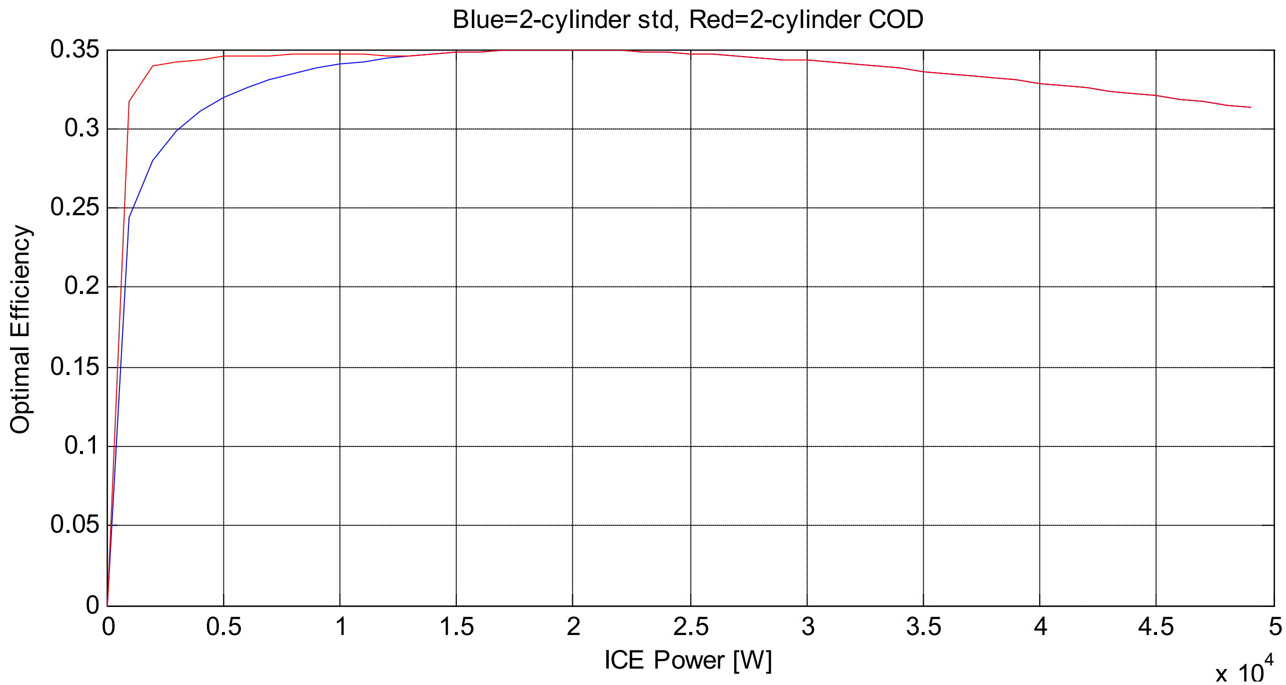
- Cylinder deactivation via free valve control

- 4-stroke, 6-stroke, 8-stroke ...

Optimized efficiency



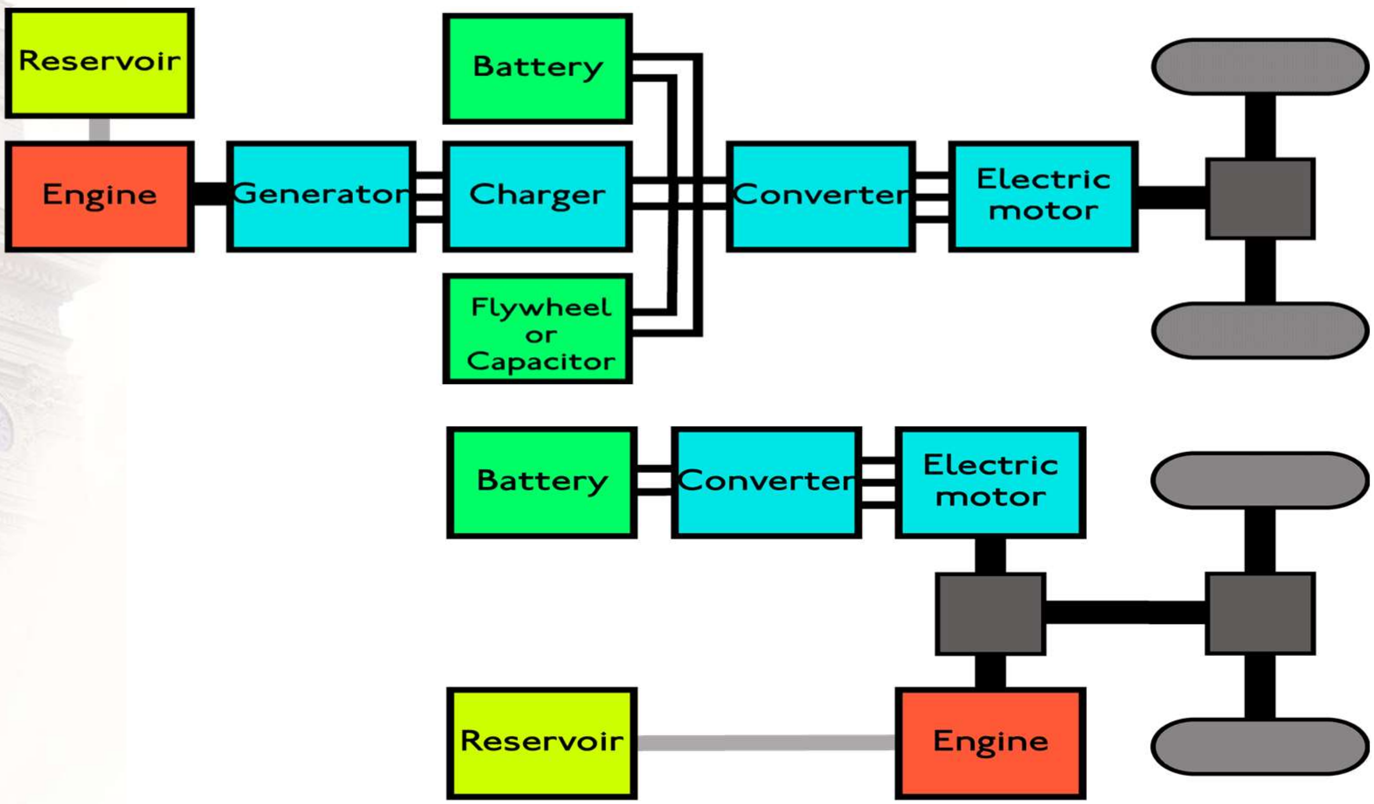
Max efficiency



Secondary Energy Storage selection

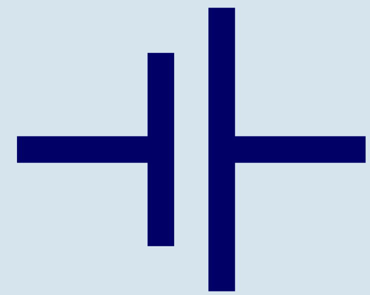
- Why electric?
  - Efficient secondary energy converters (Electrical machines)
  - Safe, quiet, flexible installation
  - Increasing need for Auxilliary electric power
  - High torque density of Electrical Mchines
    - *Up to 30 Nm/kg*
    - *ICE: <2 Nm/kg*

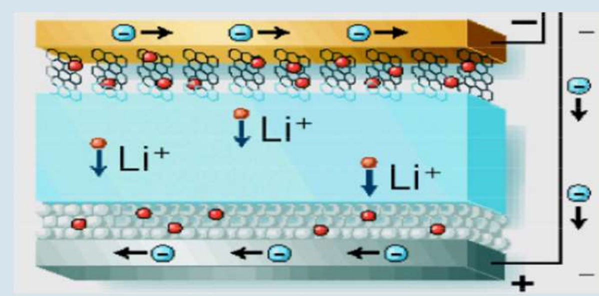
Secondary energy storage – Hybridisation



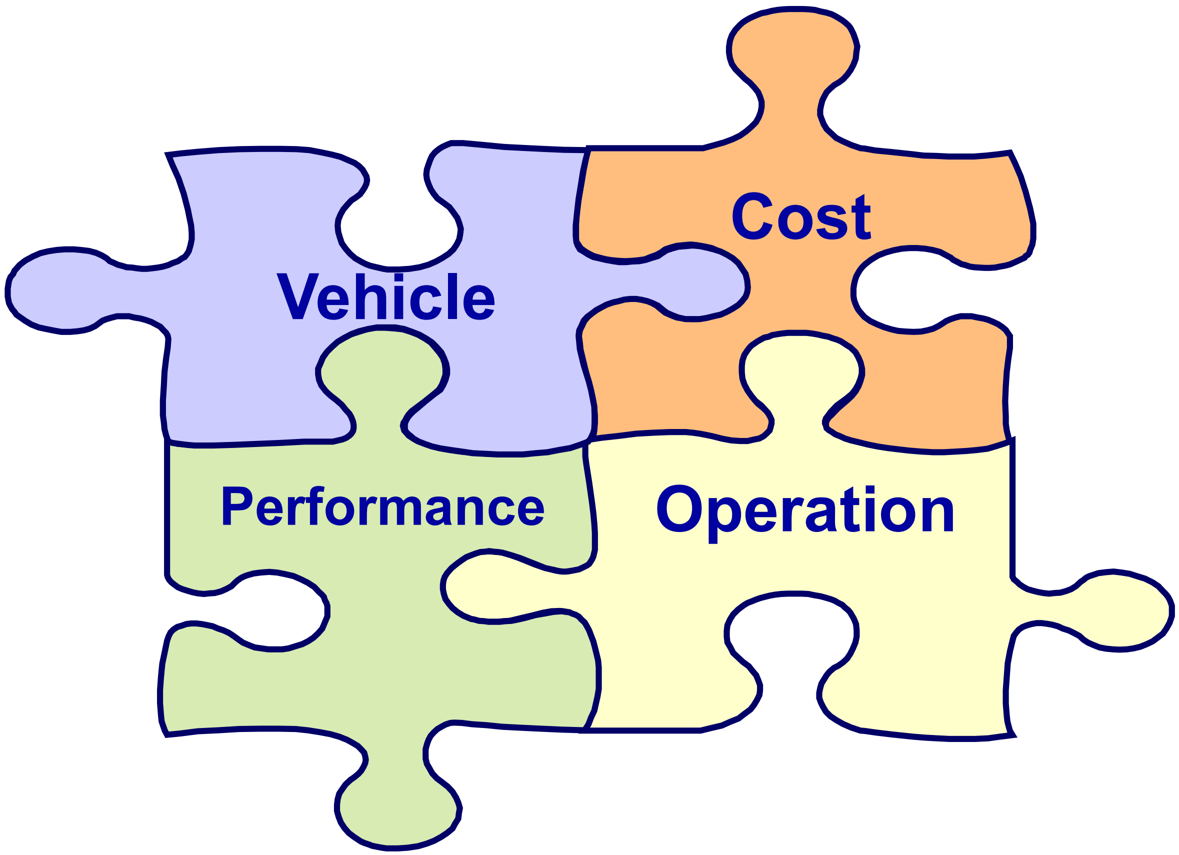
Energy Storage Systems

How does a battery look?

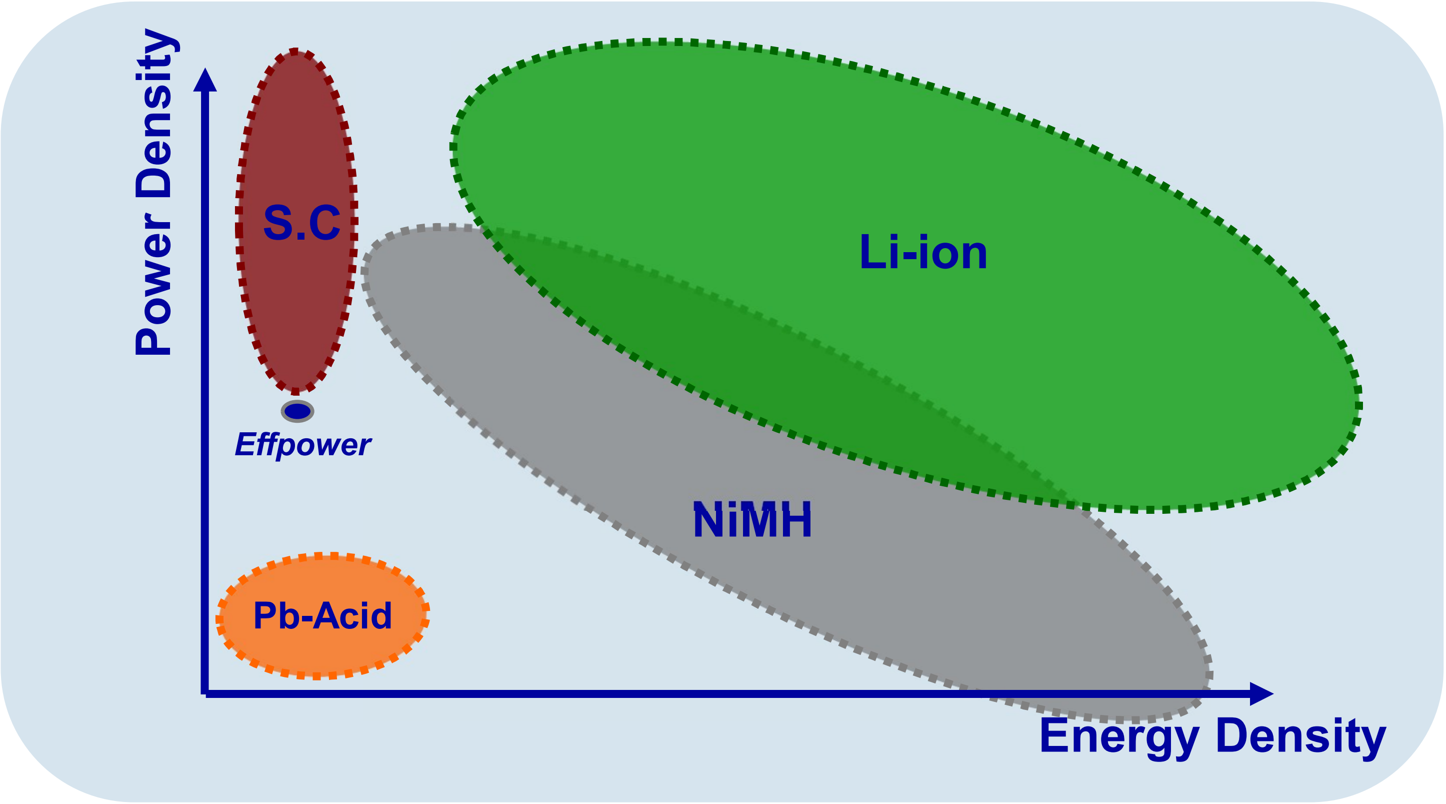




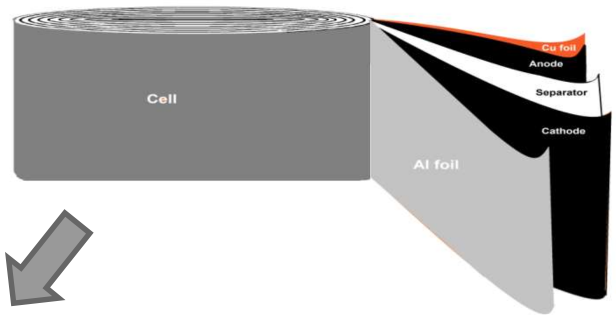
Design criteria

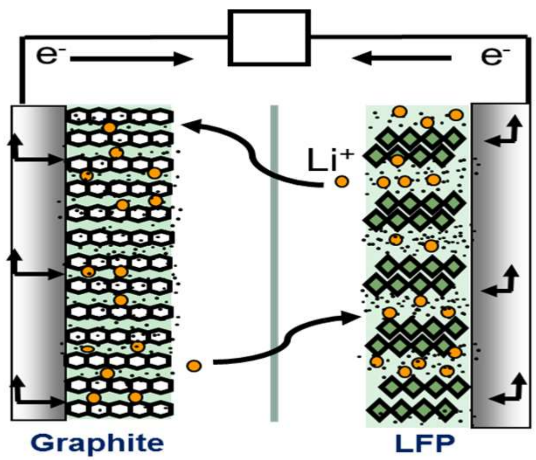


Performance



What is a battery cell?





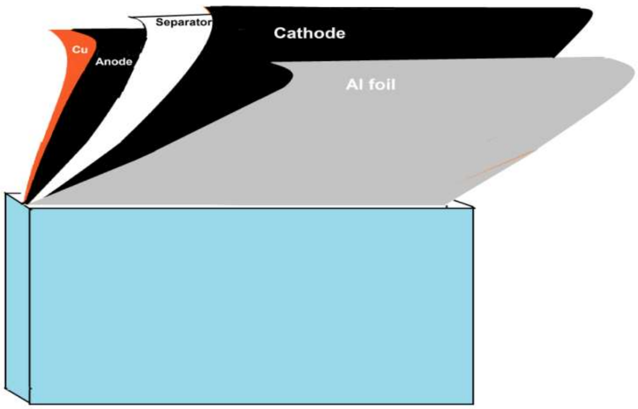
Different cell formats

Prismatic

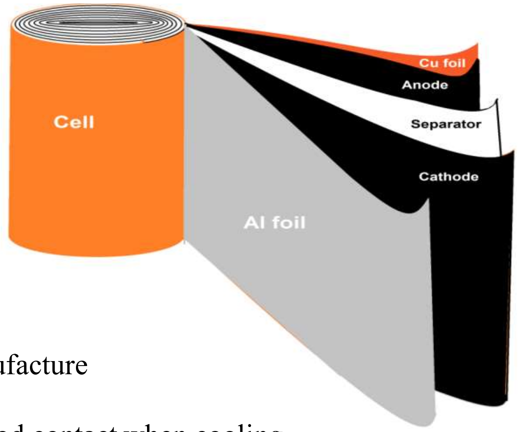
Cylindrical

Pouch

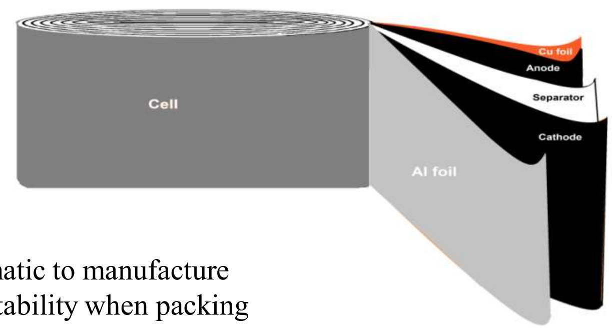
Same principle inside



Prismatic
Simplier building block for module
More mechanically stable than pouch
(still needs mechanical support in the module)



Cylindrical
Easy and cheap to manufacture
More difficult to pack
More difficult to get good contact when cooling



Pouch
Cheaper than prismatic to manufacture
Need mechanical stability when packing

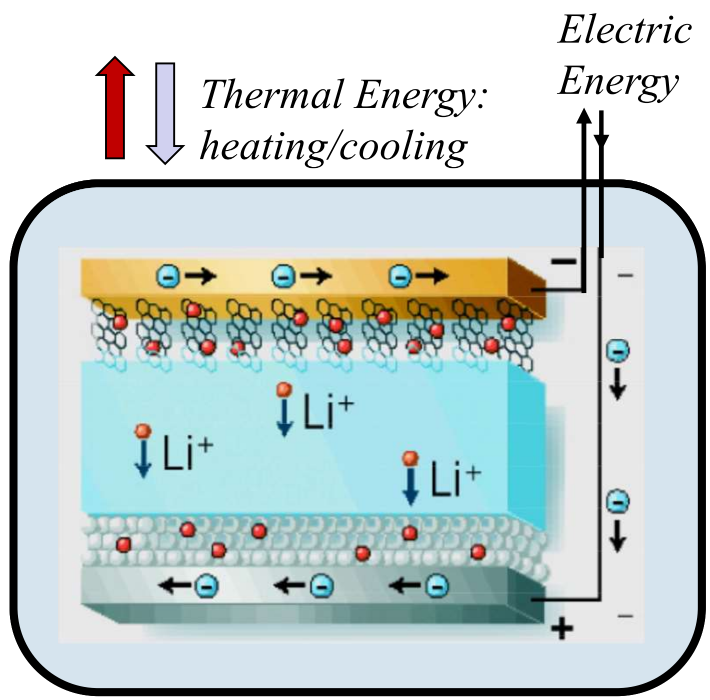
Short introduction to Battery Characteristics

The Battery Cell – a Chemical Reactor

Closed
no material transfer

Controlled
no spontaneous reaction
different energy levels

Reversible
rechargeable
high efficiency



Short introduction to Battery Characteristics

SOC – state-of-charge

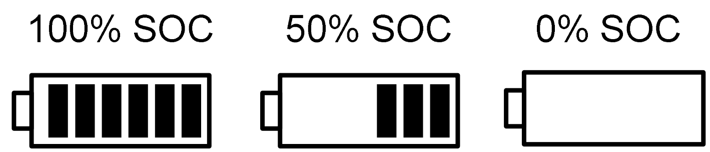
- Charge level related to reference capacity[1]
- 0-1 or 0-100%

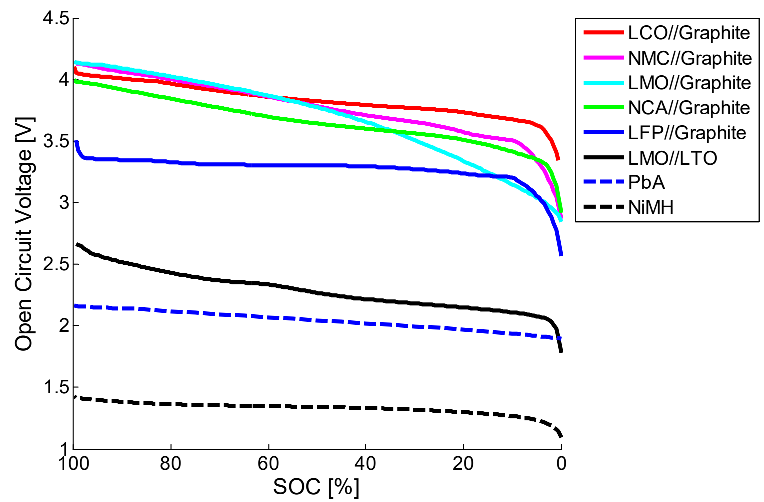
OCV – open circuit voltage

- Battery voltage at rest°
- Measured after 15-60min rest period[2]
- Affected by temperature, age & hysteresis[2]

Nominal Voltage

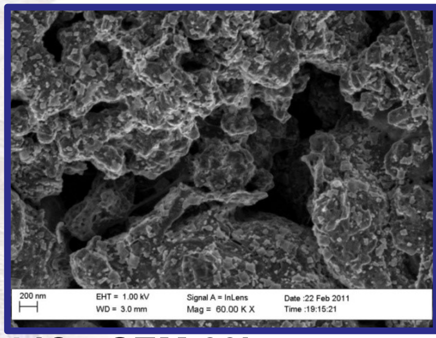
- Electrochemical voltage ≈ average OCV



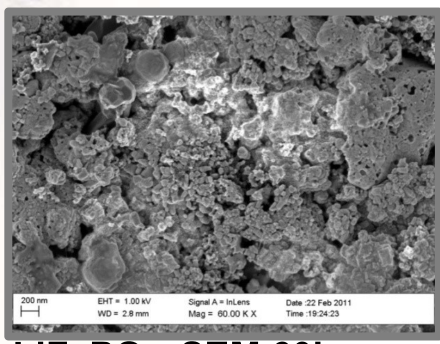


1. *Often 1C-rate discharge at +23°C*
2. *Applicable for NiMH & LFP. See separate slide.*

Physical Background & Model Design

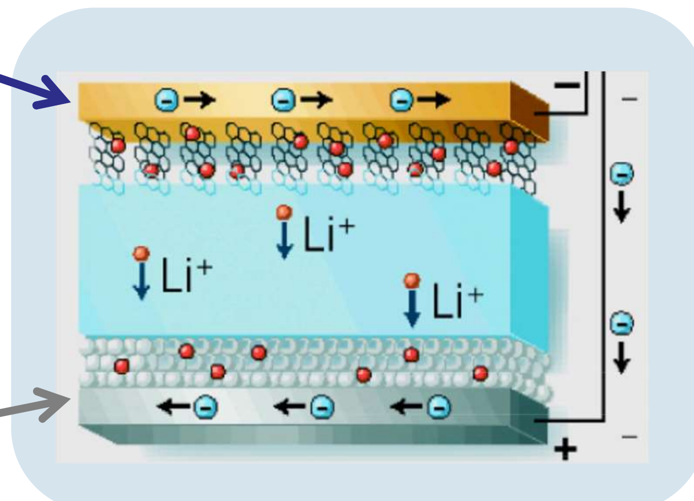


LiC_6: SEM 60k

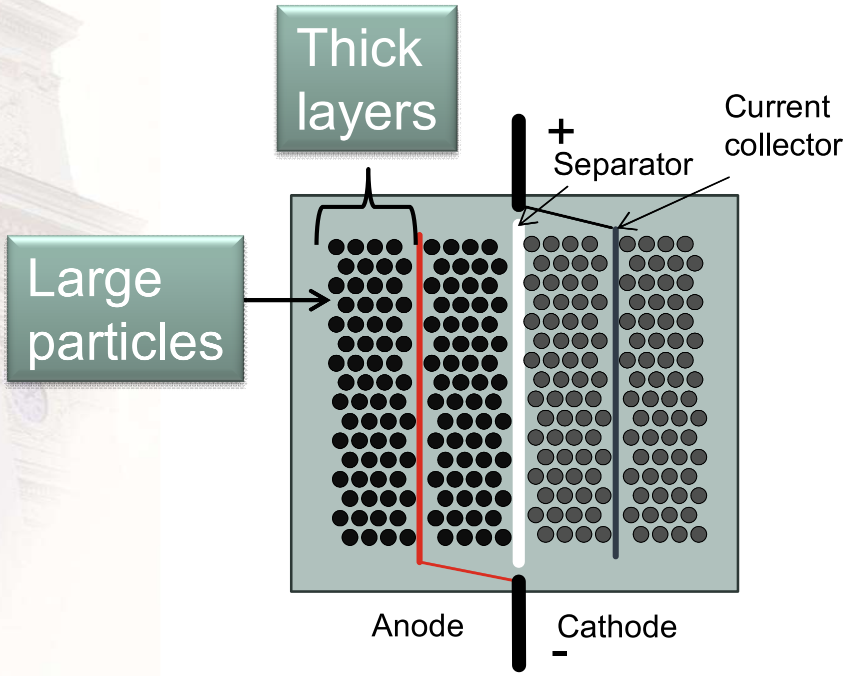


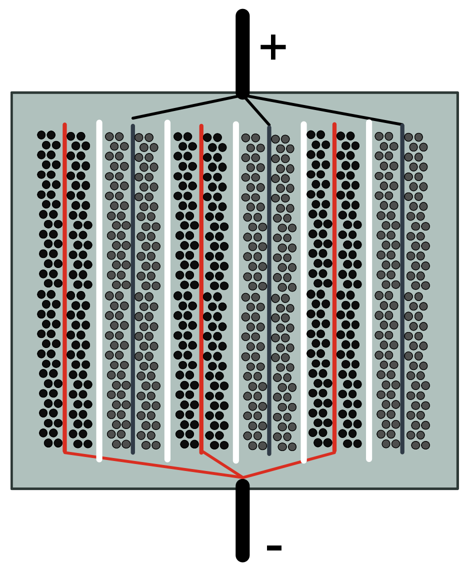
$LiFePO_4$: SEM 60k

Highly porous structure to maximise active area



Power- vs. Energy- optimised



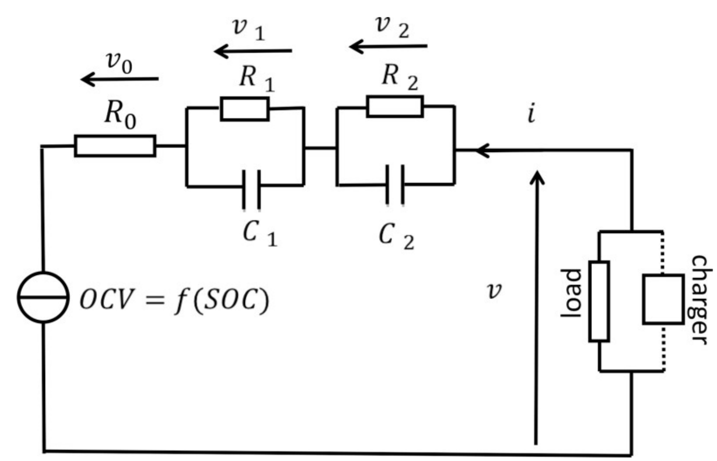


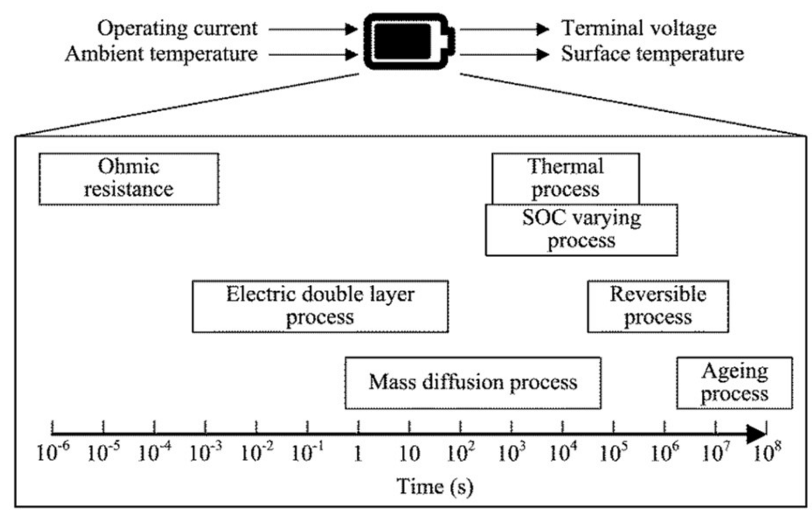
Battery Cell Properties

- All parameters are non-linear
- Strong dependence on SOC, temperature, current rate & direction, and history.
- OSV = Open Circuit Voltage
- R0, R1, C1 describe the battery resistance, charger transfer and “double layer effect”1
- R2, C2 describe the diffusion2 effect

1) *The first layer, the surface charge (either positive or negative), consists of ions adsorbed onto the object due to chemical interactions. The second layer is composed of ions attracted to the surface charge via the Coulomb force, electrically screening the first layer.* [*https://en.wikipedia.org/wiki/Double_layer_(surface_science)*](https://en.wikipedia.org/wiki/Double_layer_(surface_science))
2) *Movement of Lithium ions*

https://www.sciencedirect.com/science/article/pii/S0360544217317127#fig1

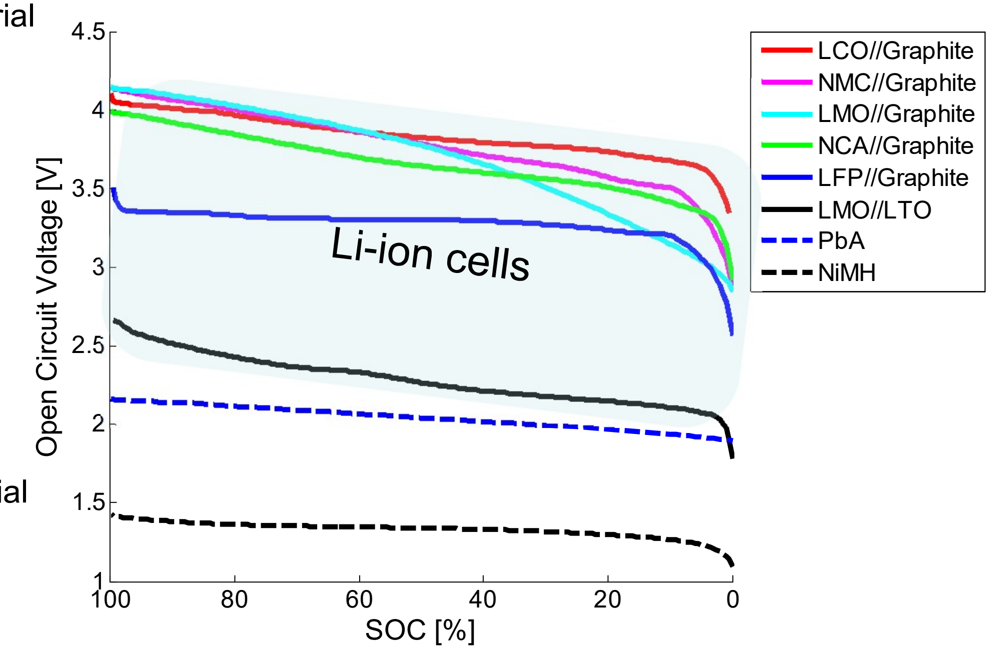




http://www.mdpi.com/1996-1073/9/6/444

Short introduction to Battery Characteristics

- Cell capacity [Ah]
  - Defined by cell design & choice of active material
    Typical range: 5-100Ah
- Cell voltage [V]
  - Defined by choice of active material
    Typical range 1-4.5V
- Cell energy [Wh]
  - Energy = Capacity • Voltage
    Typical range: 5-400Wh
- Cell power [W]
  - Power = Voltage • Current
    Limited by cell design & choice of active material
    Typical range: 5-5000W



Short introduction to Battery Characteristics

SOH – state-of-health

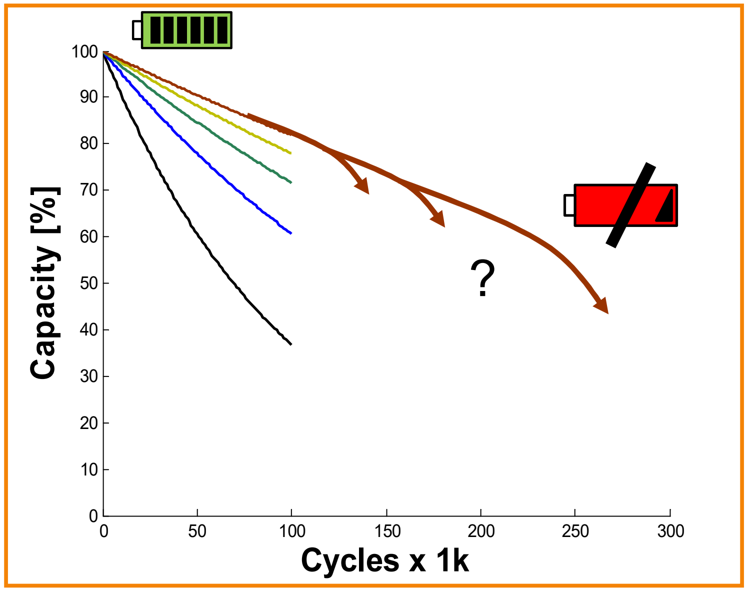
- Actual capacity related to reference capacity
- 0-1 or 0-100%, sometimes 80-100%
- No standard definition

BOL – beginning of life

- Fresh / unused battery

EOL – end of life

- Aged battery with insufficient performance
- Can be defined by capacity, energy, power etc.
  No standard definition

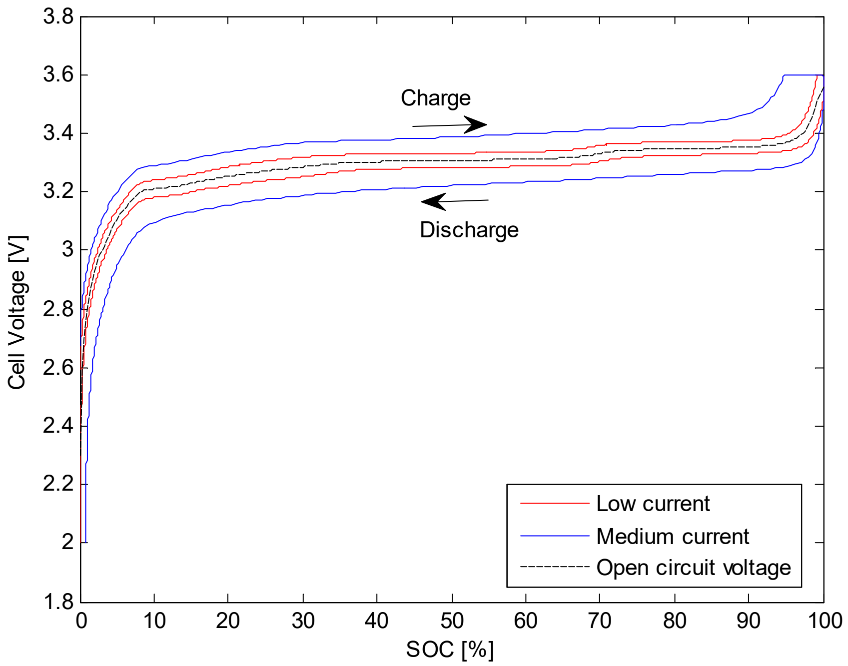


Short introduction to Battery Characteristics

Cell Voltage = f(...)

- Material Selection
- State of Charge (SOC)
- Current / power
- Temperature
- Age

→No equilibrium / steady-state



Short introduction to Battery Characteristics

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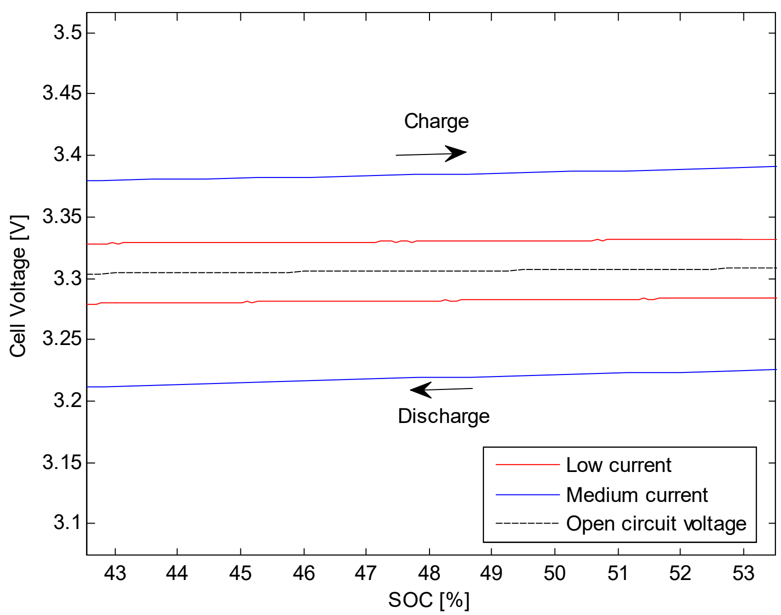
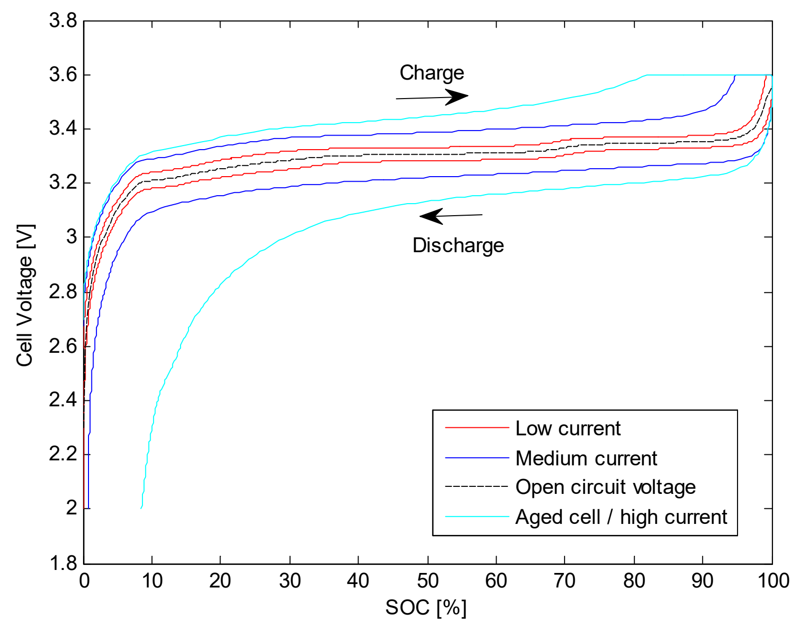


Short introduction to Battery Characteristics

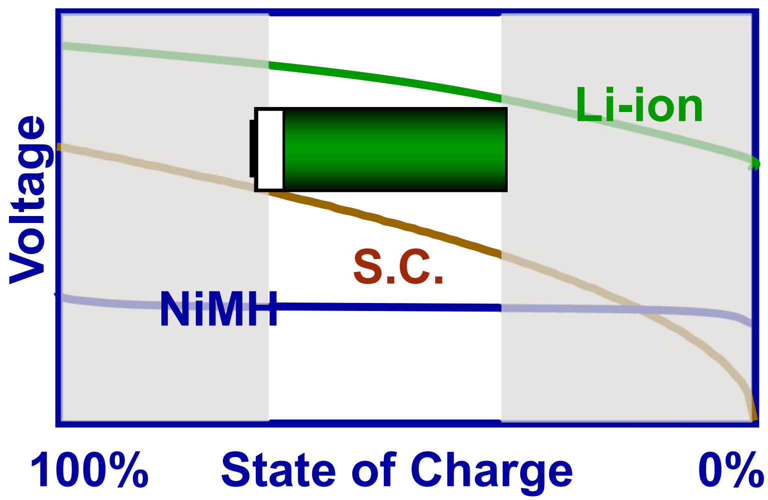
Cell Voltage = f(...)
- Material Selection
- State of Charge (SOC)
- Current / power
- Temperature
- Age

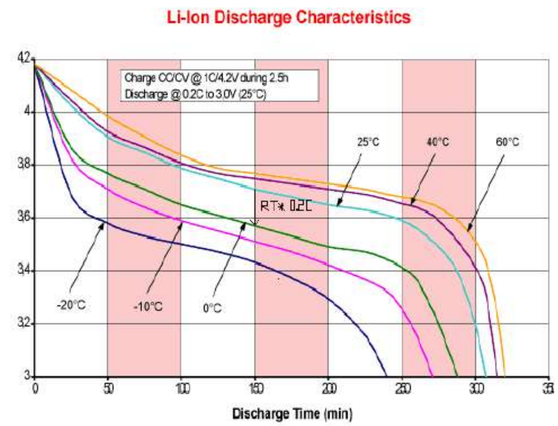
→No equilibrium / steady-state

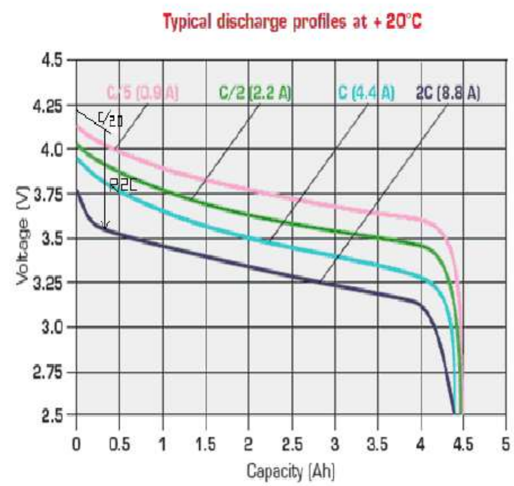


State of Charge

- C-rate = P[kW] / W[kWh]
  - C=1: 1 h full charge
  - C=2: 30 min full charge





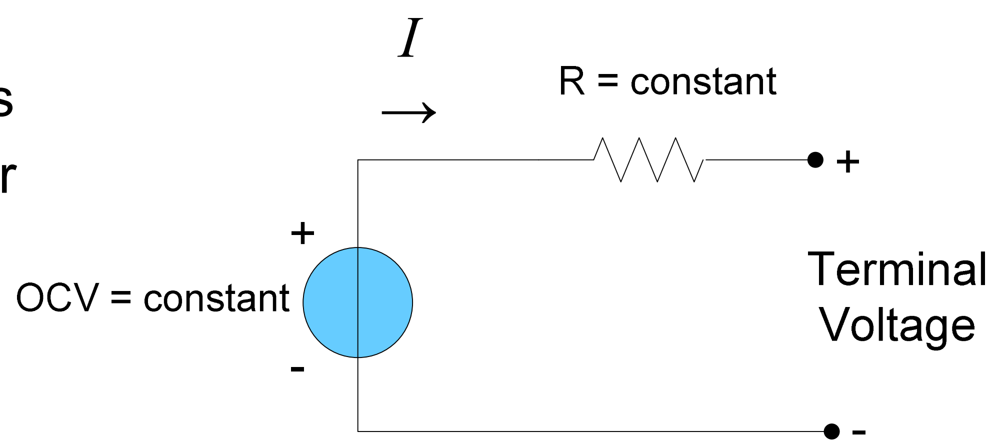


https://www.researchgate.net/figure/Discharge-curves-for-different-technologies-and-different-batteries_fig1_224395476

Applied Modelling: Performance & Accuracy

<u>Simple Battery model</u>

- Constant parameters
- Very fast, suitable for optimisation



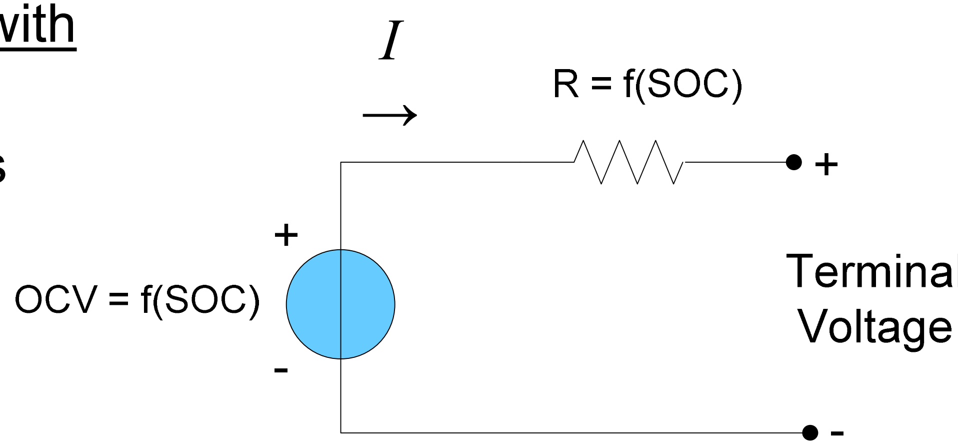
- Very limited accuracy

$$P = U \cdot I = U\left(\frac{U - OCV}{R}\right) = \frac{1}{R}\left(U^2 - U \cdot OCV\right)$$

Applied Modelling: Performance & Accuracy

<u>Simple Battery model with SOC</u>

- Simple look-up tables
- Still fast, suitable for optimisation



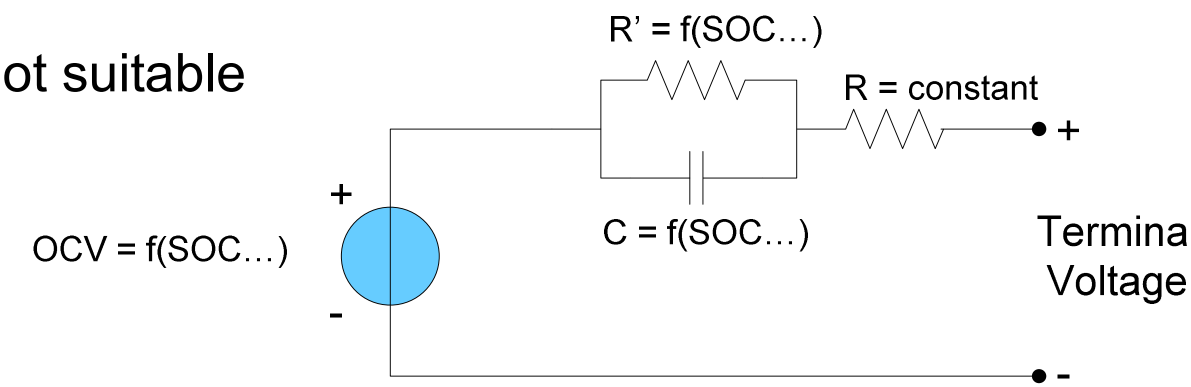
$$U = OCV(SOC) - R(SOC) \cdot I$$

- Still limited accuracy

Applied Modelling: Performance & Accuracy

Enhanced battery model with SOC & t

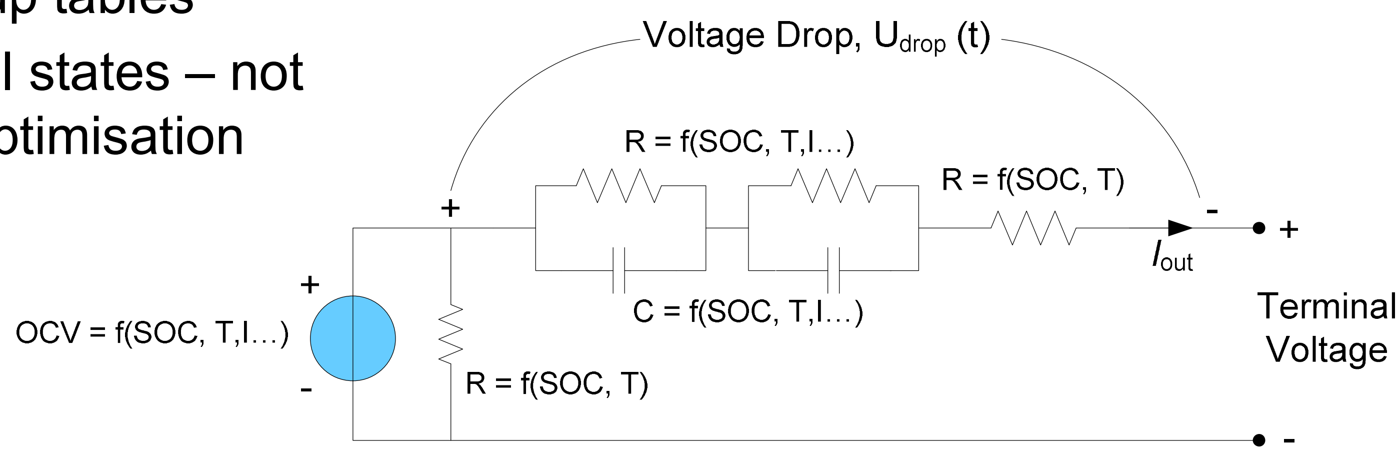
- Simple look-up tables
- Two internal states – not suitable for optimisation



Applied Modelling: Performance & Accuracy

Advanced battery model with SOC, T & t

- Simple look-up tables
- Three internal states – not suitable for optimisation

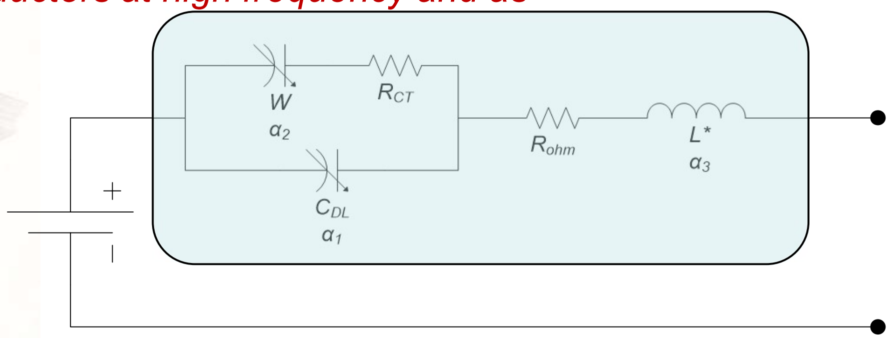


GSP Model

Applied Modelling: Performance & Accuracy

Separate high-frequency models are needed for specific cases

batteries act as inductors at high frequency and as capacitors at low



Models available form Volvo GTT-ATR for specific cells upon request

$$Z = (j\omega)^{\alpha_3} L^* + R_{Ohm} + \frac{1}{\frac{1}{R_{ct} + \frac{1}{C_W (j\omega)^{a_2}}} + \frac{1}{C_{dl}(j\omega)^{a_1}}} \quad [Ohm]$$

Battery simulation model : I

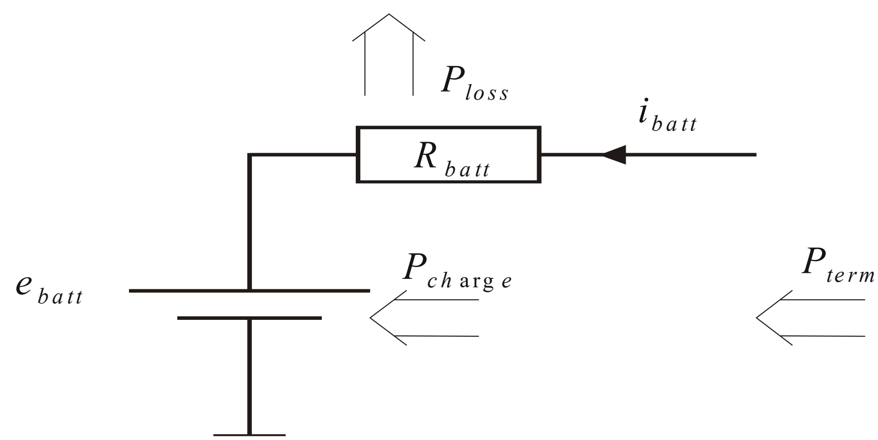
$$P_{term} = (e_{batt} + R_{batt} \cdot i_{batt}) \cdot i_{batt} = e_{batt} \cdot i_{batt} + R_{batt} \cdot i_{batt}^2$$

$$i_{batt} = -\frac{e_{batt}}{2 \cdot R_{batt}} \pm \sqrt{\left(\frac{e_{batt}}{2 \cdot R_{batt}}\right)^2 + \frac{P_{term}}{R_{batt}}}$$

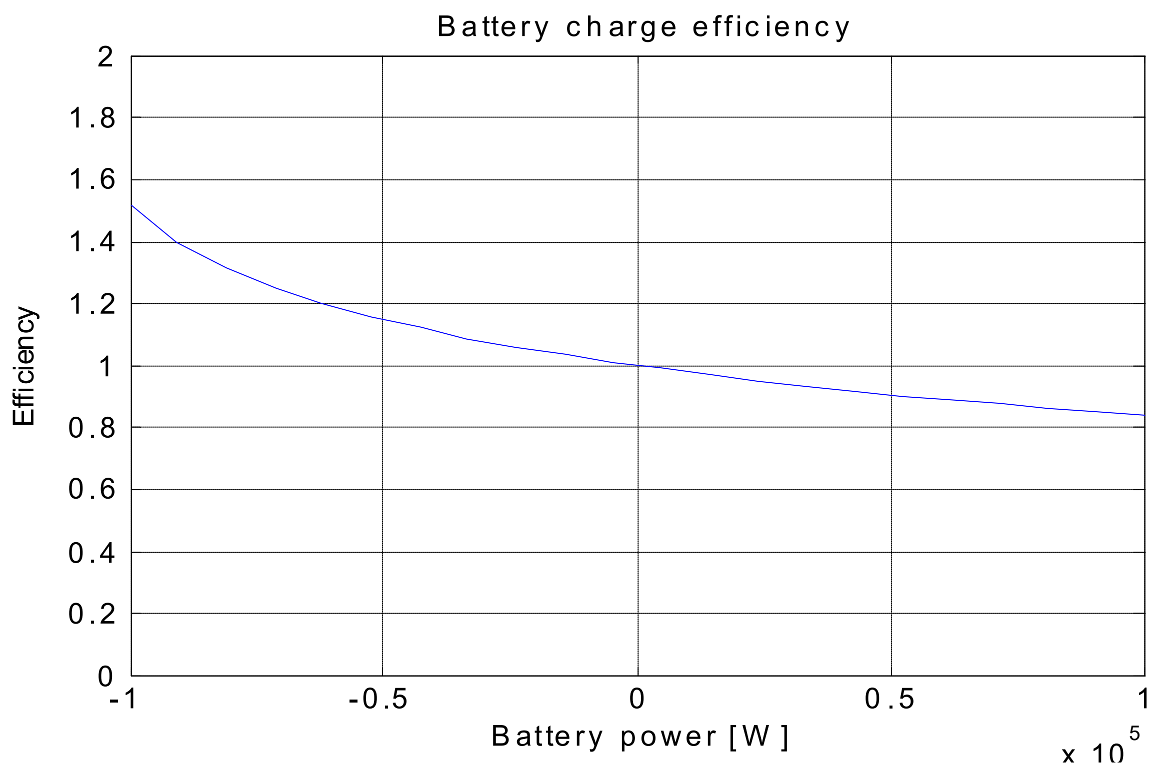
$$P_{loss} = R_{batt} \cdot i_{batt}^2$$

$$P_{charge} = P_{term} - P_{loss}$$

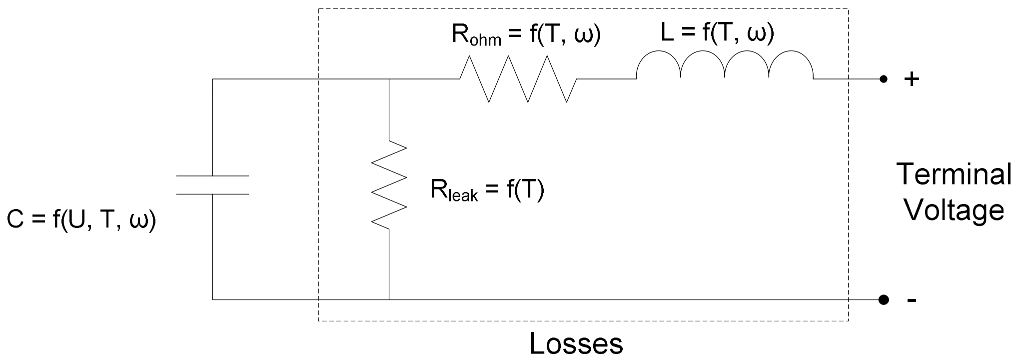
$$\eta_{batt} = \frac{P_{charge}}{P_{term}}$$



Battery Simulation model : II



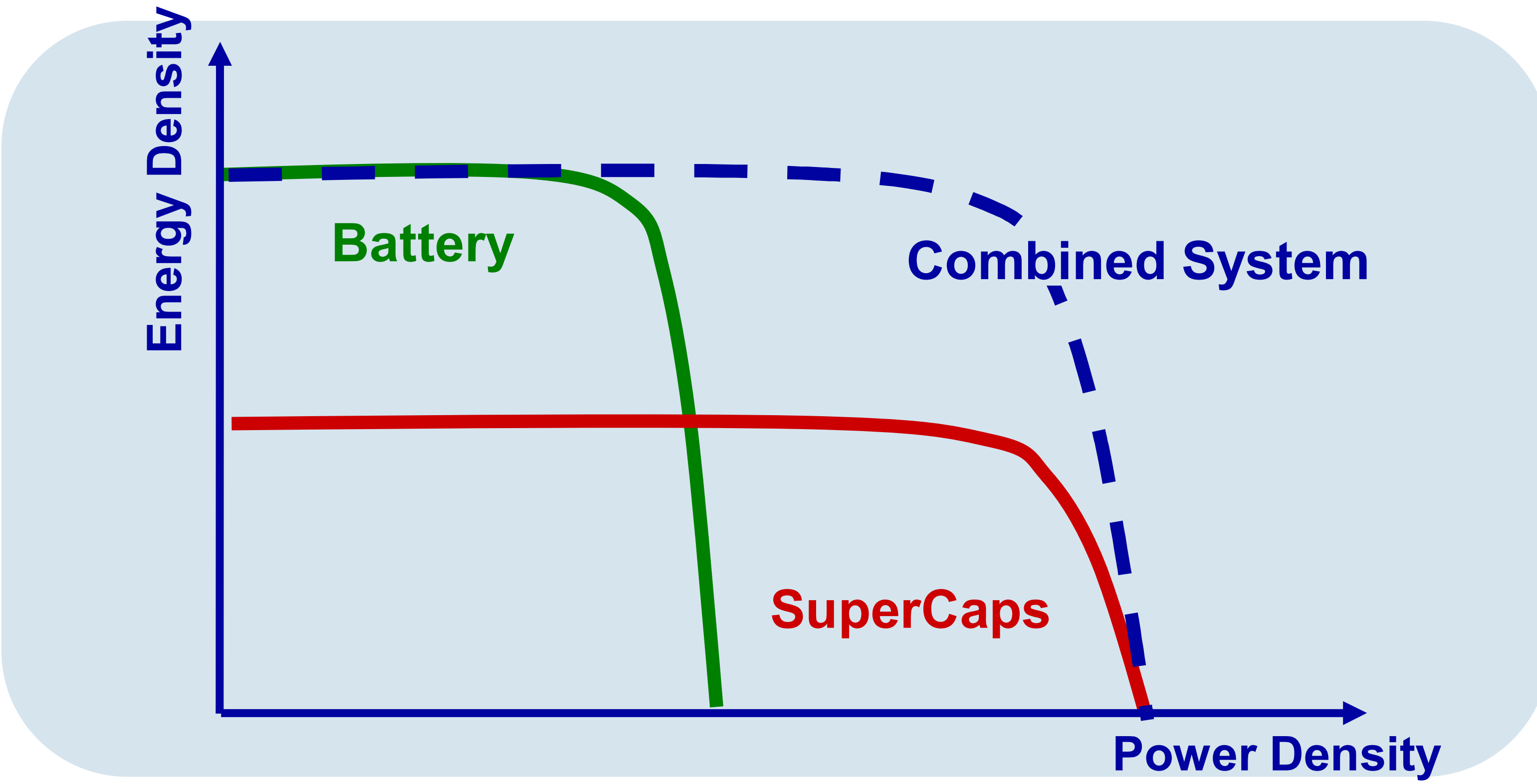
Super Capacitor Cell Properties



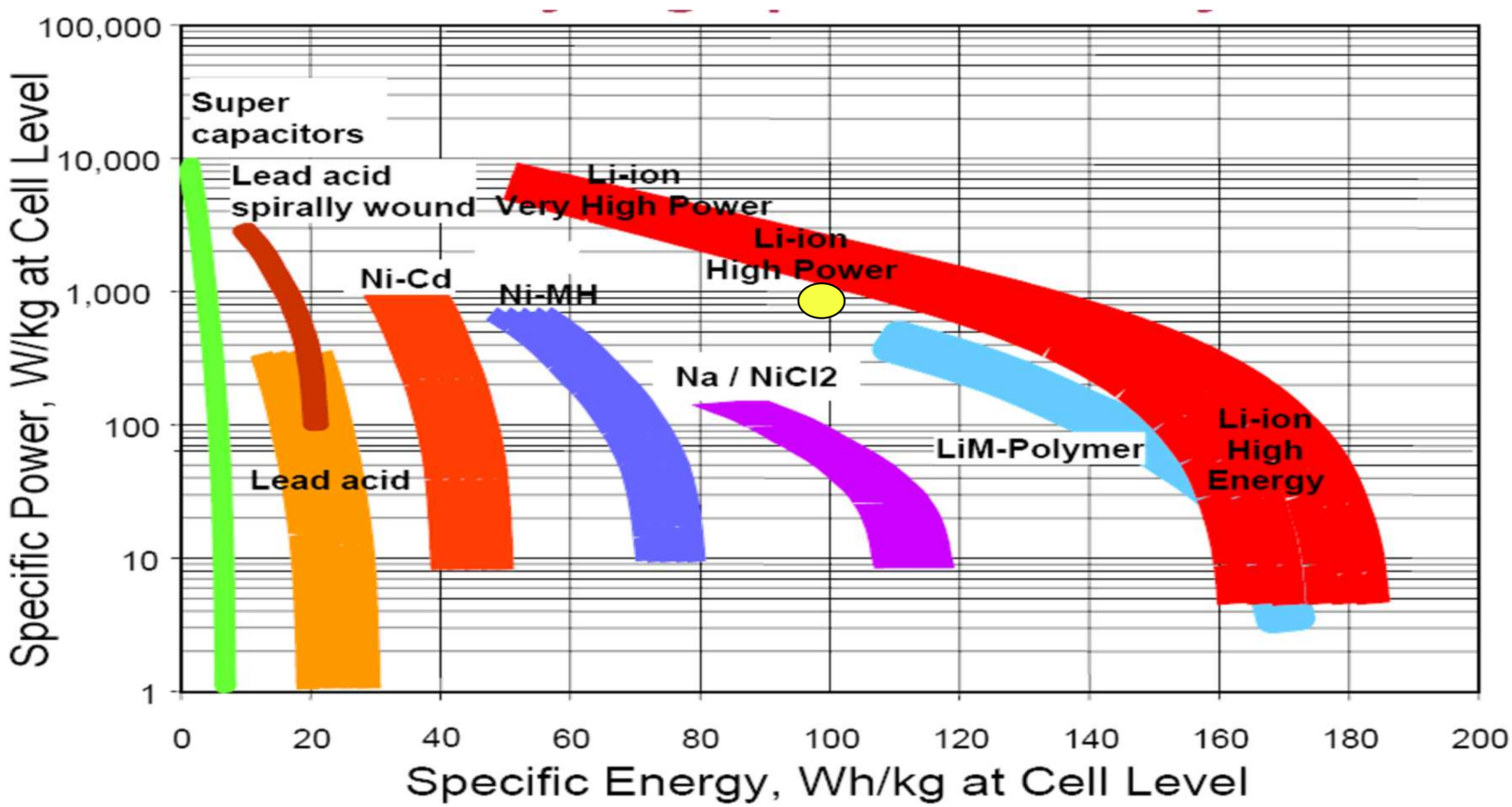
- Fewer non-linear elements
- Strong dependance on SOC & temperature only

”Semi” Steady-State Operation!

Combined Energy Storage System

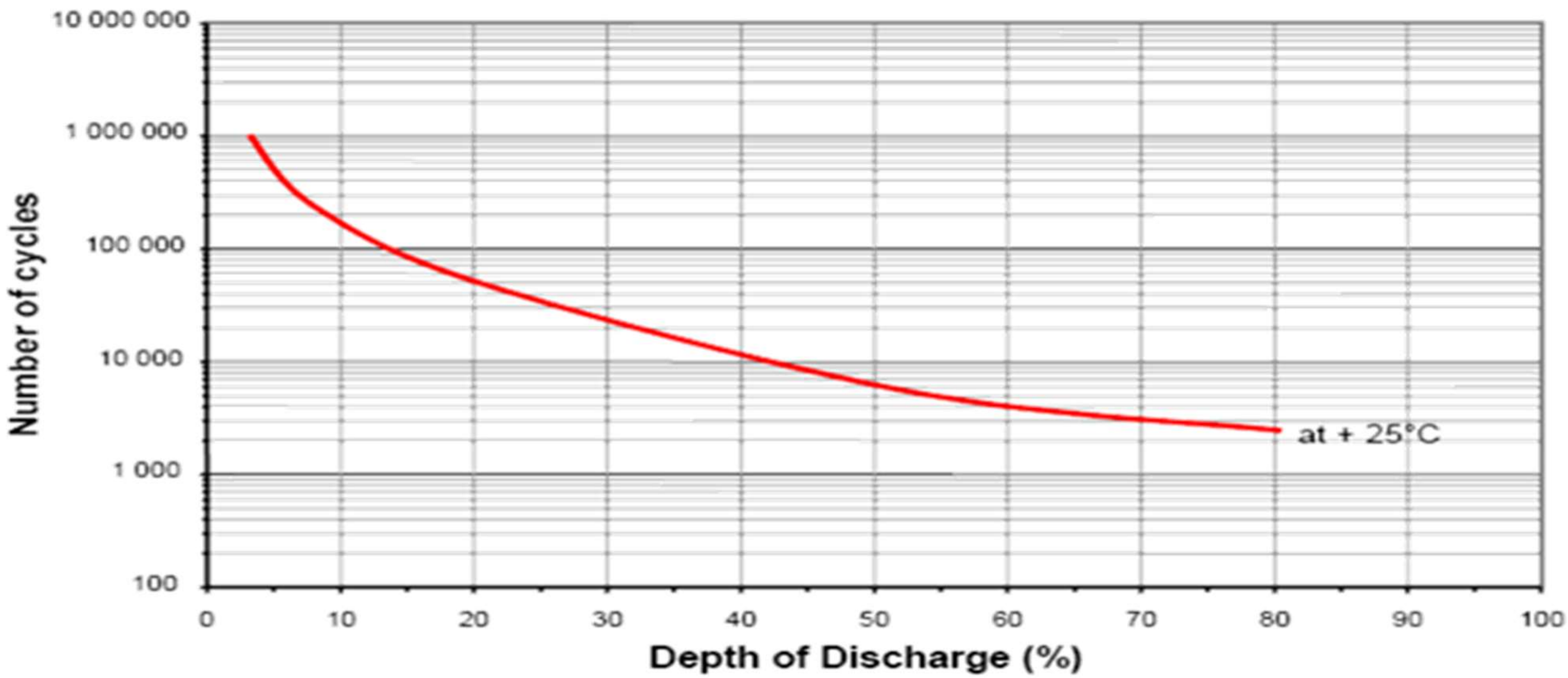


SAFT data



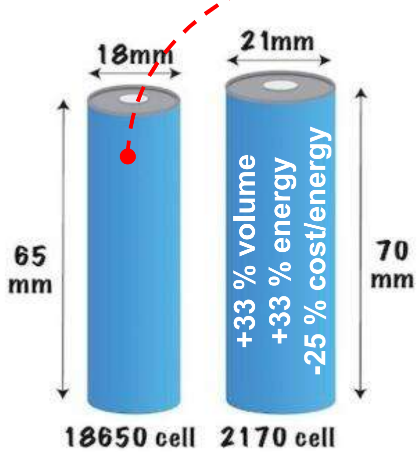
Specific Power, W/kg at Cell Level
Specific Energy, Wh/kg at Cell Level
100,000
10,000
1,000
100
10
1
0
20
40
60
80
100
120
140
160
180
200
Super capacitors
Lead acid spirally wound
Li-ion Very High Power
Li-ion High Power
Ni-Cd
Ni-MH
Na / NiCl2
LiM-Polymer
Li-ion High Energy
Lead acid

SAFT Lithium teknologi

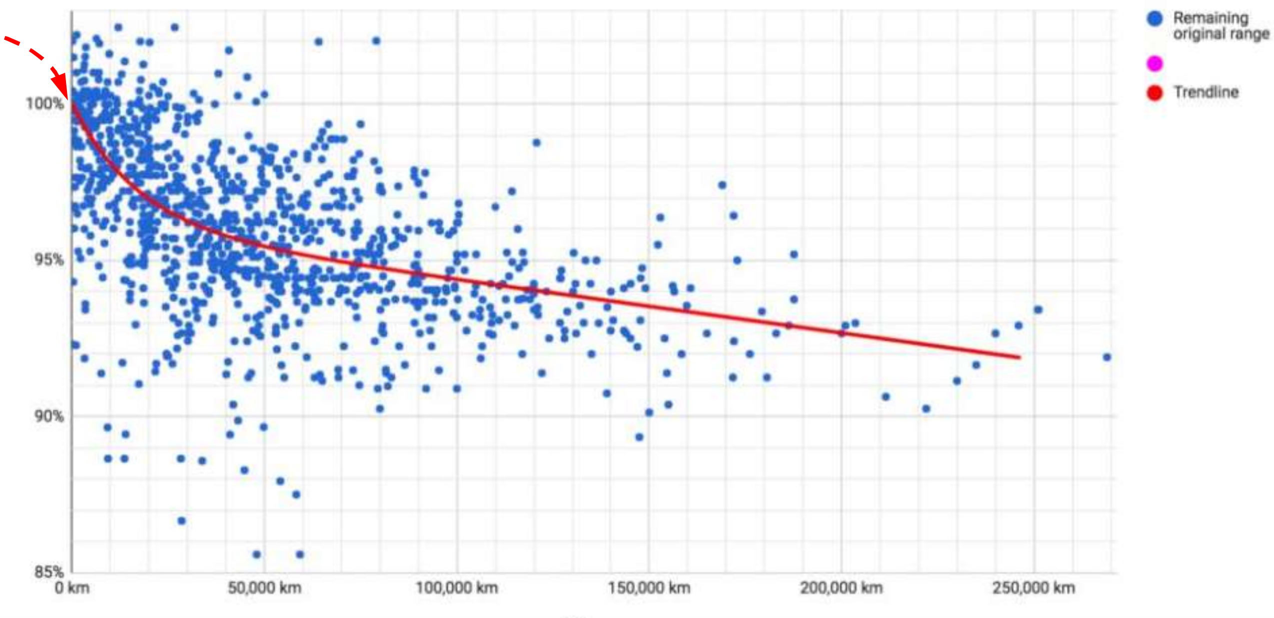


Tesla Model S&X, Milage vs remaining battery capacity

- Based on the 18650 cell.



- Model 3 use the 2170 cell



Tesla Model S and Model X battery degradation chart [Credit: Matteo via Maarten Steinbuch]

https://www.teslarati.com/tesla-battery-life-80-percent-capacity-840km-1-million-km/

Battery Lifetime : II

- Calculate the total converted energy as:

  *Wconv=Wbatt*DoD/100*NoC*

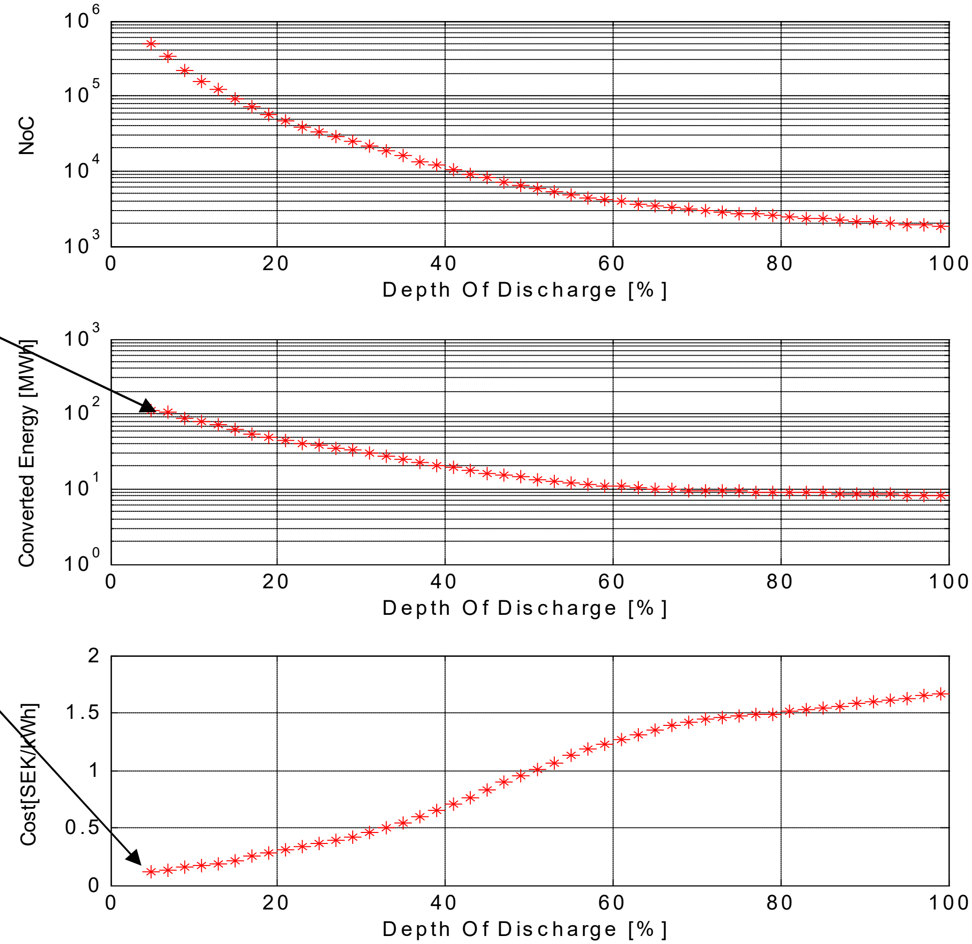
- And the battery cost per kWh converted energy as:

  *SEKperkWh = CostPerkWh*Wbatt / Wconv*

  CostPerkWh = 3000 [SEK]

Battery Lifetime : III

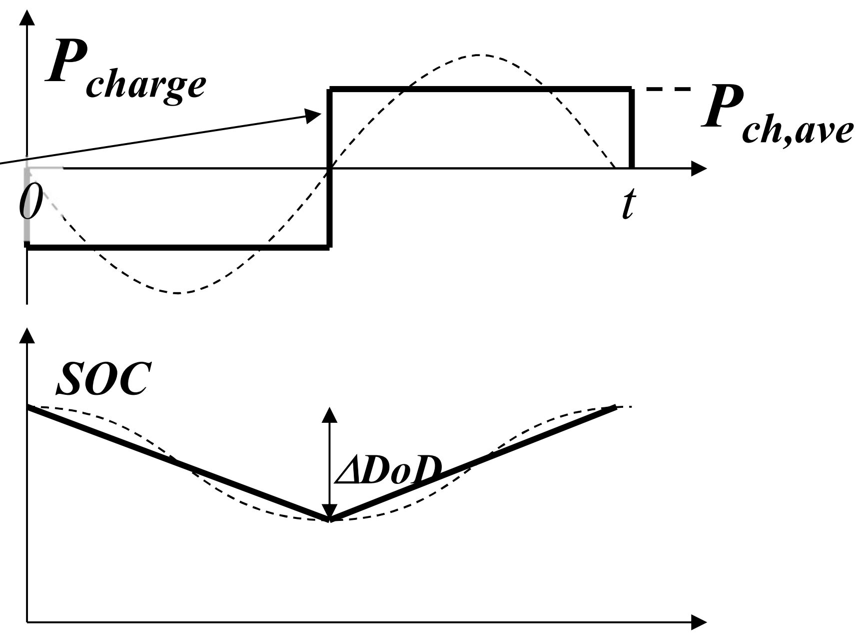
- Note! – The total converted energy falls fast with increased DoD !!!
- The cost per converted kWh increases rapidly with increased DoD



Battery Lifetime : IV

- Assume that DoD is driven by a constant charge Power
- then… :

$$\Delta DoD = \frac{P_{ch,ave} \cdot \frac{t}{2}}{W_{batt}} \cdot 100$$



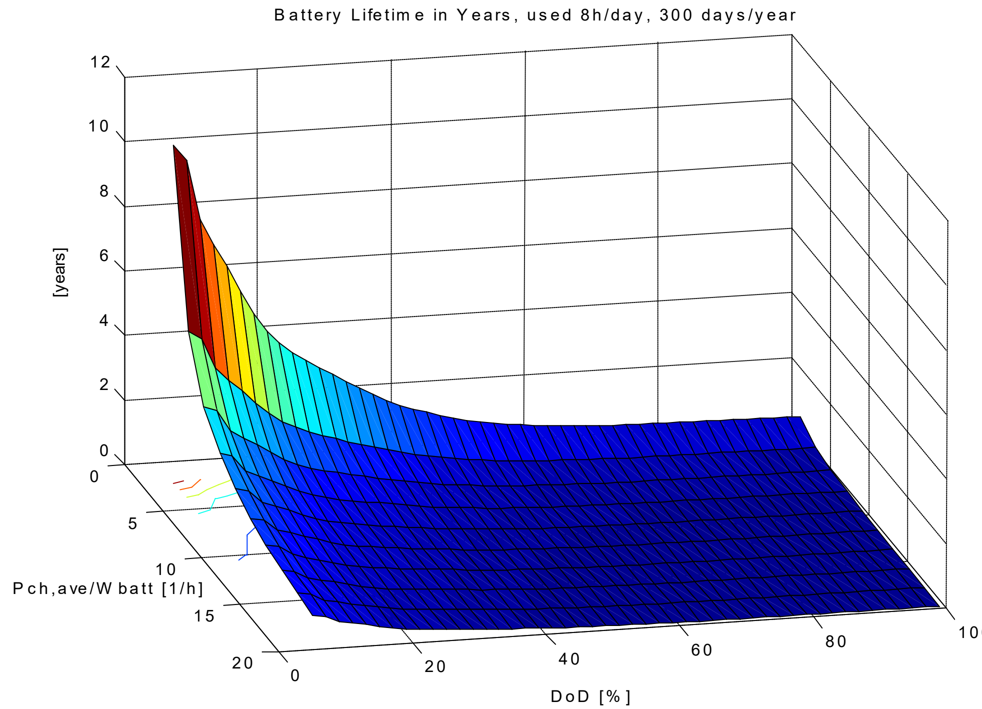
Battery Lifetime : V

- *The battery lifetime can be calculated as:*

$$\Delta DoD = \frac{P_{ch,ave} \cdot \frac{t}{2}}{W_{batt}} \cdot 100$$

$$Lifetime = \frac{DoD \cdot W_{batt} \cdot 2}{P_{ch,ave} \cdot 100} \cdot NoC =$$

$$= \frac{DoD \cdot 2}{\frac{P_{ch,ave}}{W_{batt}} \cdot 100} \cdot NoC$$

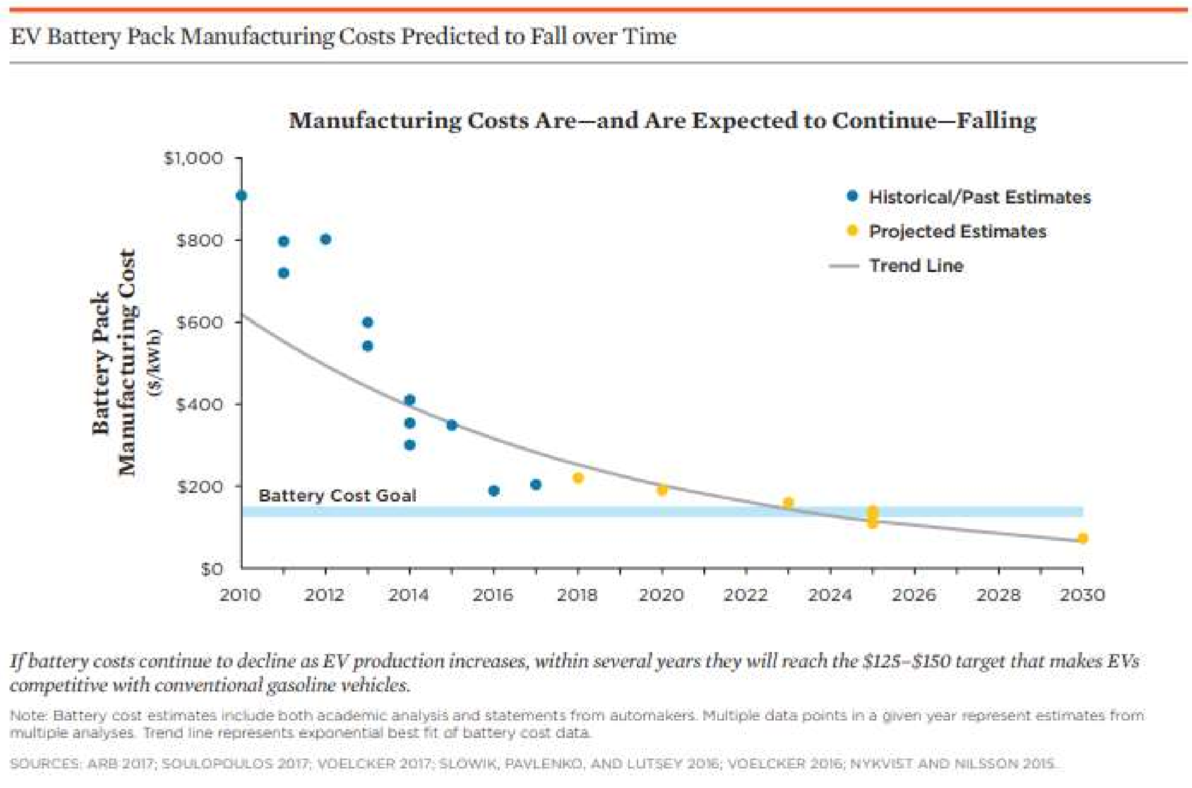


- *Now, plot the battery lifetime as a function of DoD and ($P_{ch,ave}/W_{batt}$)*
  - *Assume 8h/day, 300 days/year*

Cost and 2nd life

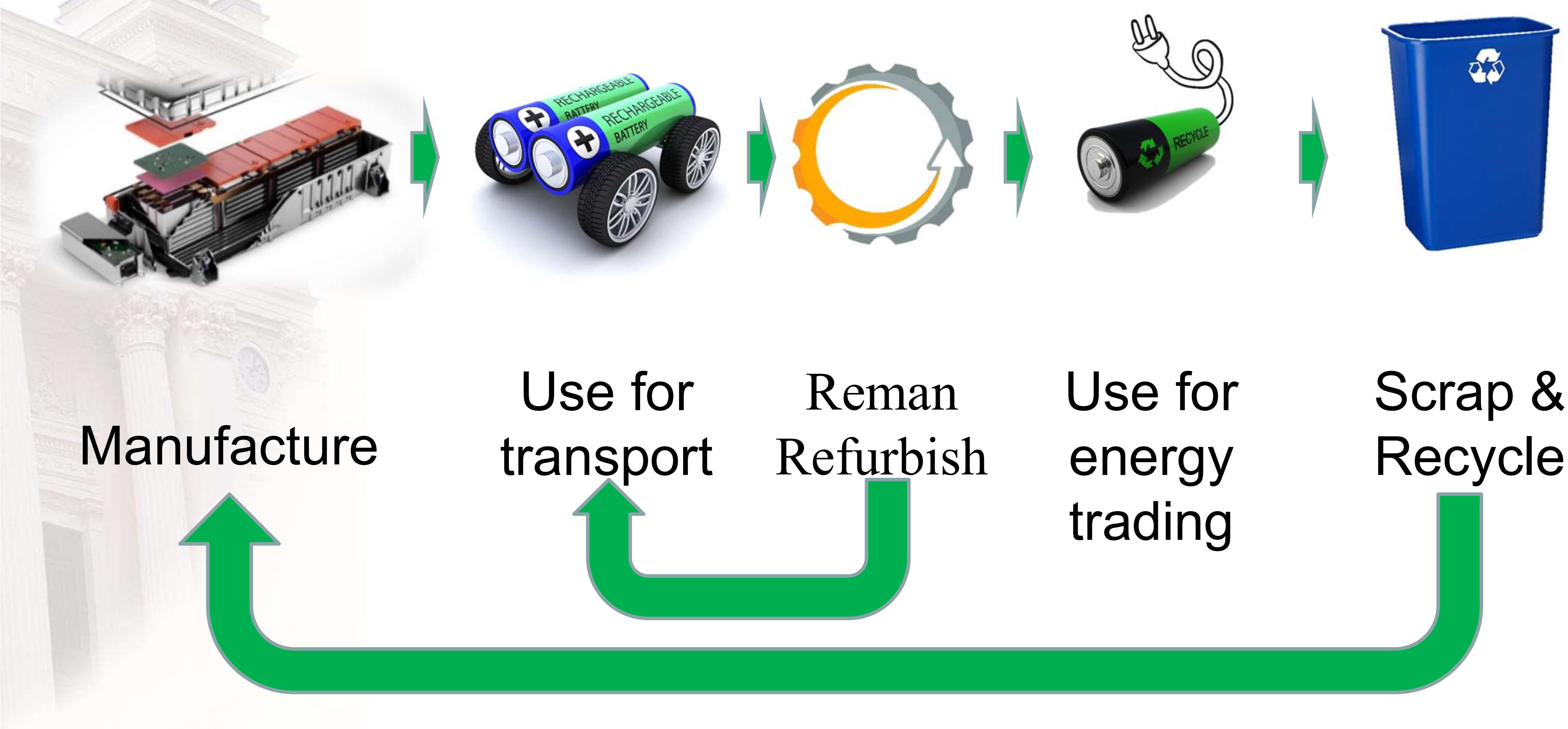
Battery Cost development

- The Cost of EV Traction Batteries is falling fast



https://www.ucsusa.org/sites/default/files/attach/2017/09/cv-factsheets-ev-incentives.pdf

The traction battery life, and business, cycle



Battery 2'nd Life

- EV's use the battery until 85-90 % capacity is left
- After leaving the vehicle, another 5...10 years of life remains.
- Grid Energy storage is an important application

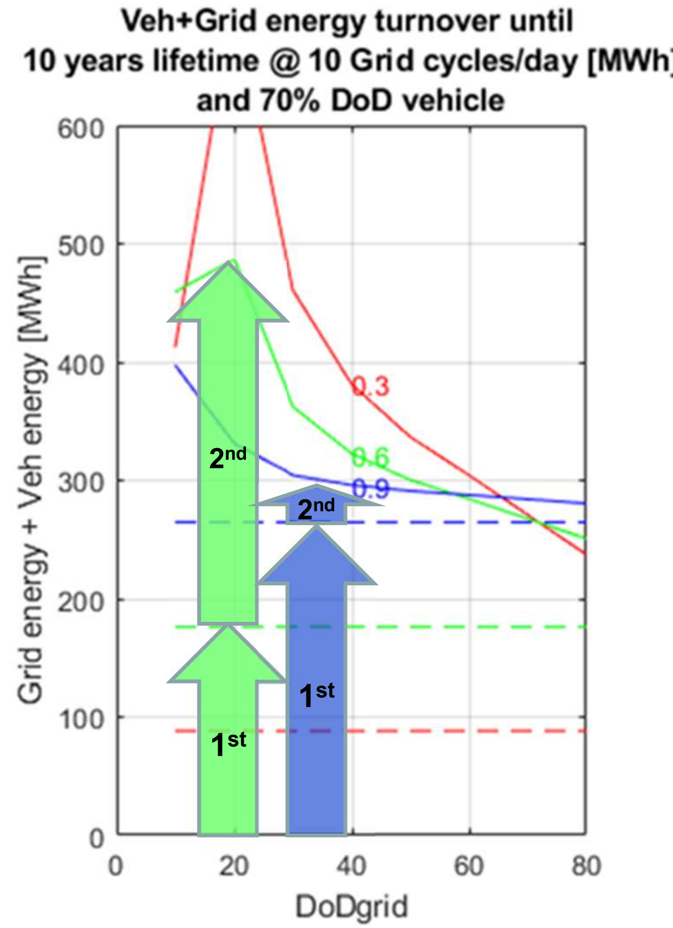
Daimler, 10's of MW and MWh

Tesla, 560 MW and129 MWh

Grid Battery Energy Storage – a Swedish perspective

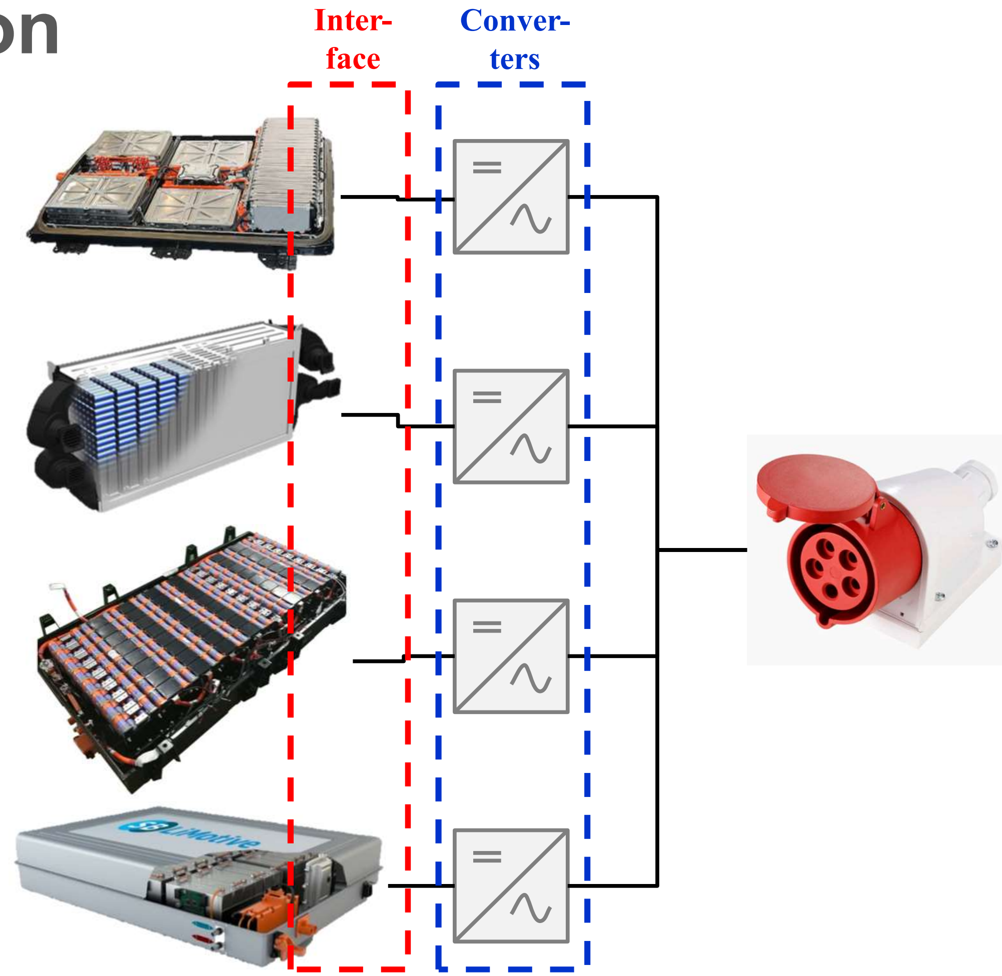
		"Fast charger and BIG Battery World"				
	# of vehicles in Sweden	Battery Size [kWh]	Battery lifetime in vehicle [years]	Battery 2'nd life in grid [years]	Grid battery energy [GWh]	Supply time @ 10 GW [h]
Cars	5 000 000	75	10	5	188	19
Heavy Trucks	50 000	500	4	2	13	1
Total					**200**	**20**

- Independent of Scenario – The **2'nd Life** batteries represent a **Significant Energy** supply for the electricity grid
- The (re)used EV battery is a **value carrier** into the electricity grid, together with renewable electricity generation



Battery 2nd life application

- In a few years we will have 1000's of batteries to handle.
- These will be more or less different ...
- These have to be joined in a systematic way
- Important to have a well defined interface and efficient converters
- "Design for 2nd life"-requirements needed on ESS HW and SW!



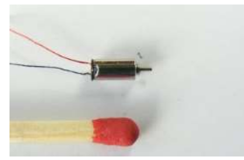
Battery Lifetime: Conclusions

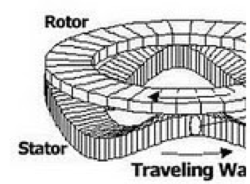
- Deep discharge of a battery costs lifetime
  - Best with less than 10 % DoD
- The battery may have a high power density BUT using it is expensive, i.e. a high power/energy ratio costs lifetime
  - Best with an average battery power in the range 3…4 x the battery energy capacity.

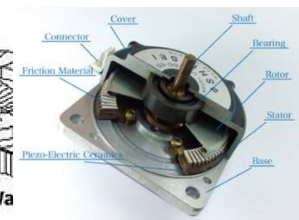
Electric Motor Drive Systems

What is an Electrical Machine?

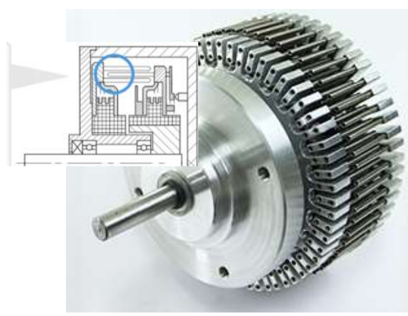
- ”A device that convertes between Electric and Mechanic energy, both ways”
- Physical principles?
  - › Some kind of field ...
    - » *Acoustic field*
    - » *Piezoelectric deformation*
    - » *Electrostatic field*
    - » *Magnetic field*





http://www.shinsei-motor.com/English/techno/index.html




Energy density, Magnetic vs Electric

$\approx 1\,[\text{Tesla}]$

$\mu_0 = 4\pi \cdot 10^{-7}$

Magnetic Energy Density $\quad \dfrac{B^2}{2\mu_0} \approx 4 \cdot 10^{5}\ [Ws/m^3]$

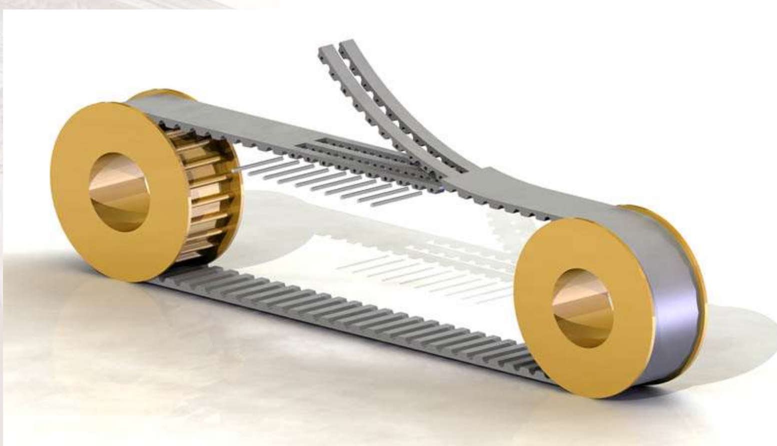
Electric Energy Density $\quad \varepsilon_0 \dfrac{E^2}{2} \approx 4 \cdot 10^{1}\ [Ws/m^3]$

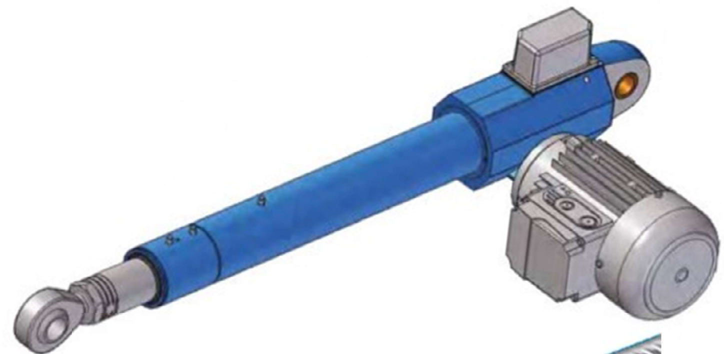
$\varepsilon_0 = 8.85 \cdot 10^{-12}$

$\approx 3\,[\text{MV/m}]$

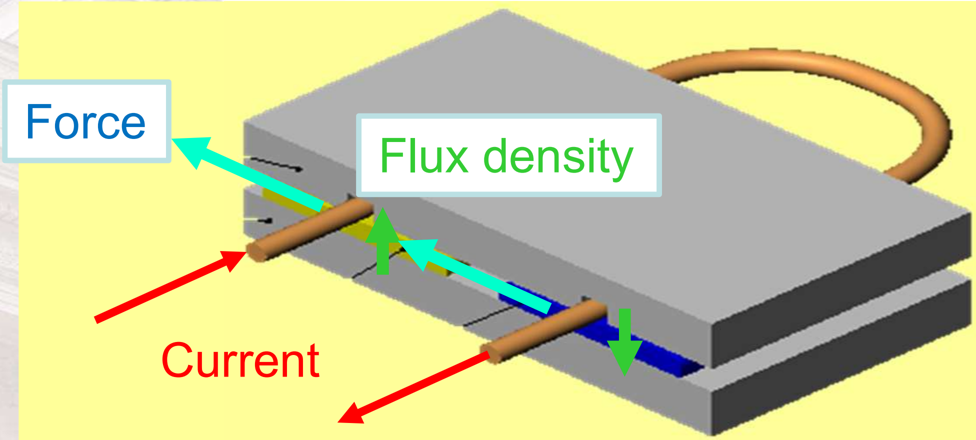
Linear Motion

- In many applications the “most wanted”
- Often translated from a rotation





Generic Force



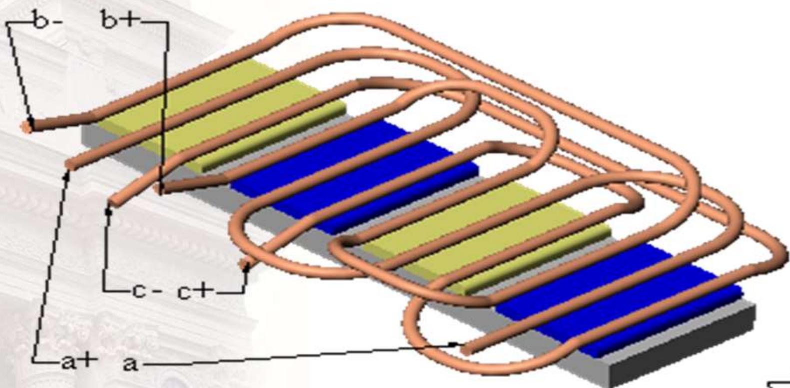
Force = Flux density * Current * length *(twice)*

Power = Force * Speed = Voltage * current

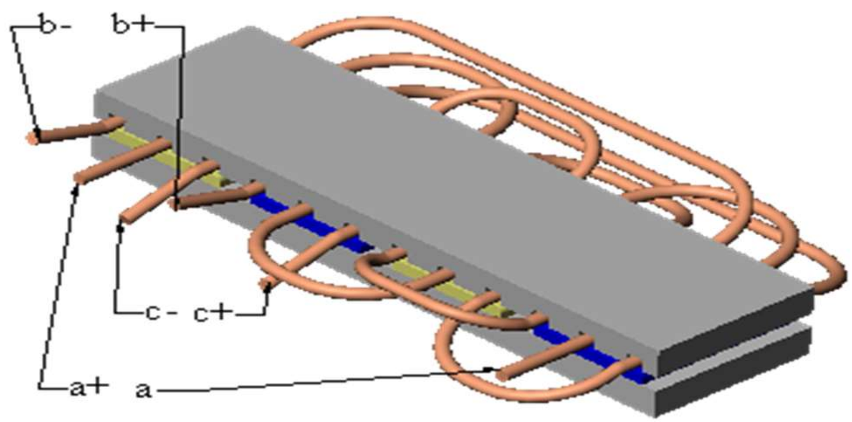
Voltage = Force *speed / current
= Flux density * length * speed

Lorentz force
= current in magnetic field

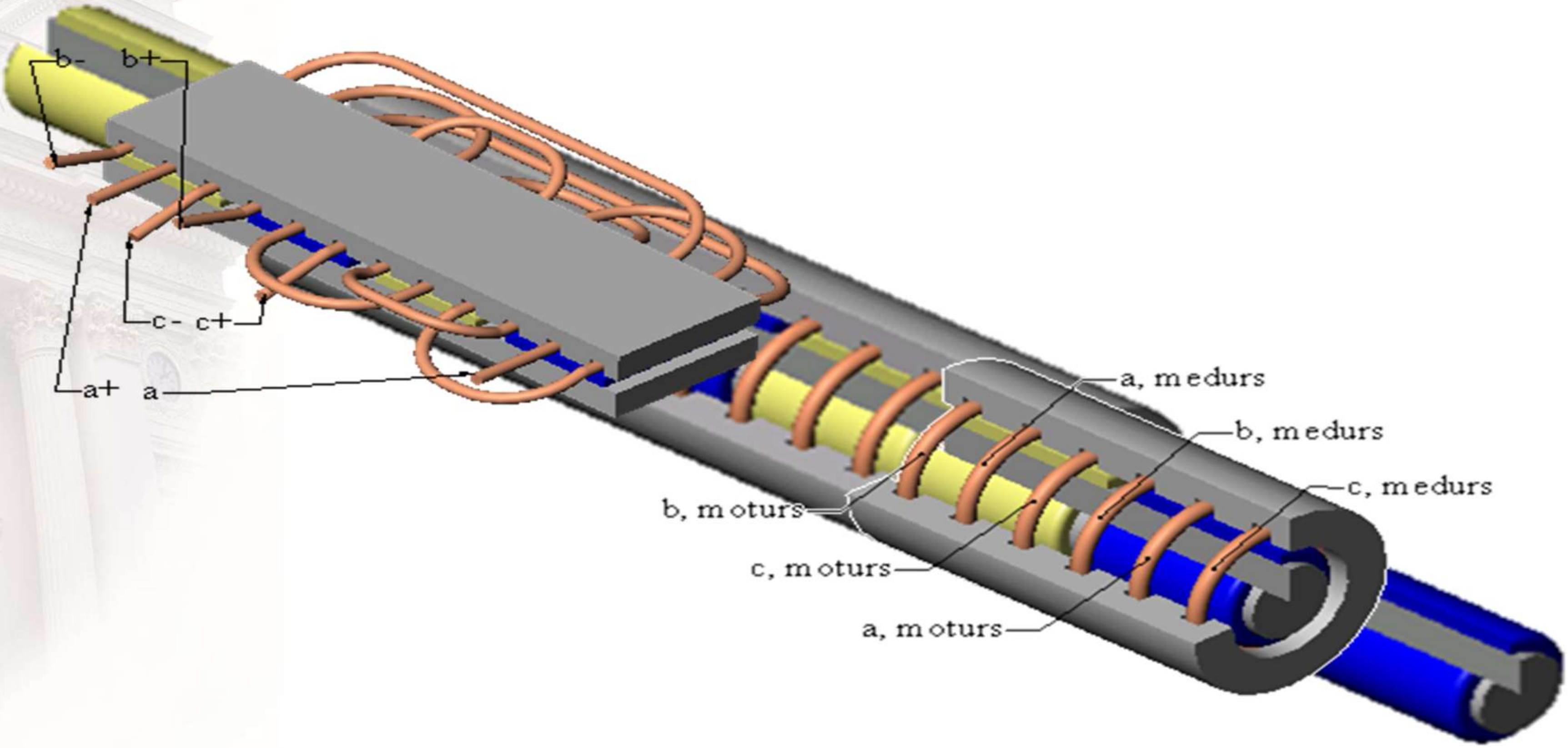
Multi Phase, otherwise it stops



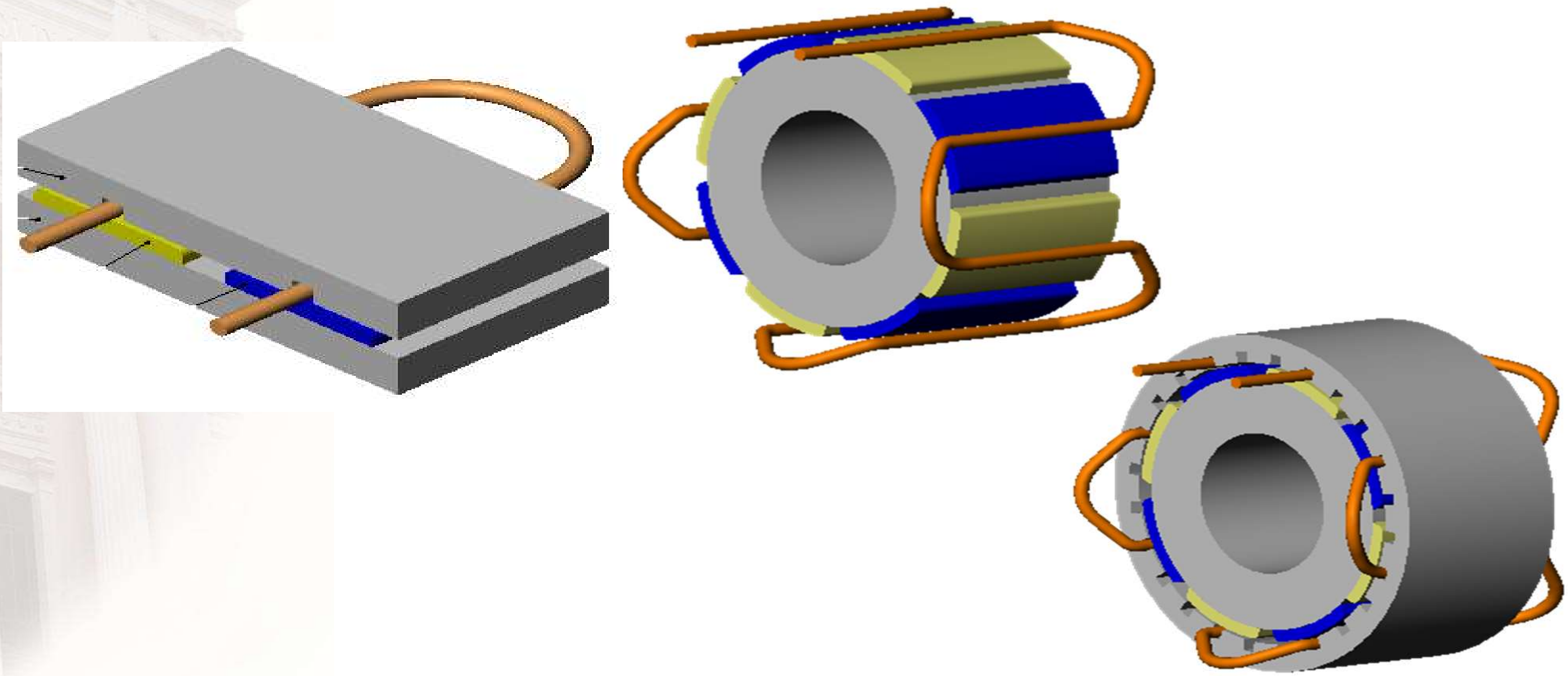
End windings don't contribute to torque, but takes a lot of space …



Linear movement from generic force



Rotating movement from generic force



Conclusions on force and movement

- *The same generic circuit accomplish both linear and rotating movement.*
- *One phase is not enough for continuous force.*
- *Qualitative:*

Voltage ~ Speed
Current ~ Force

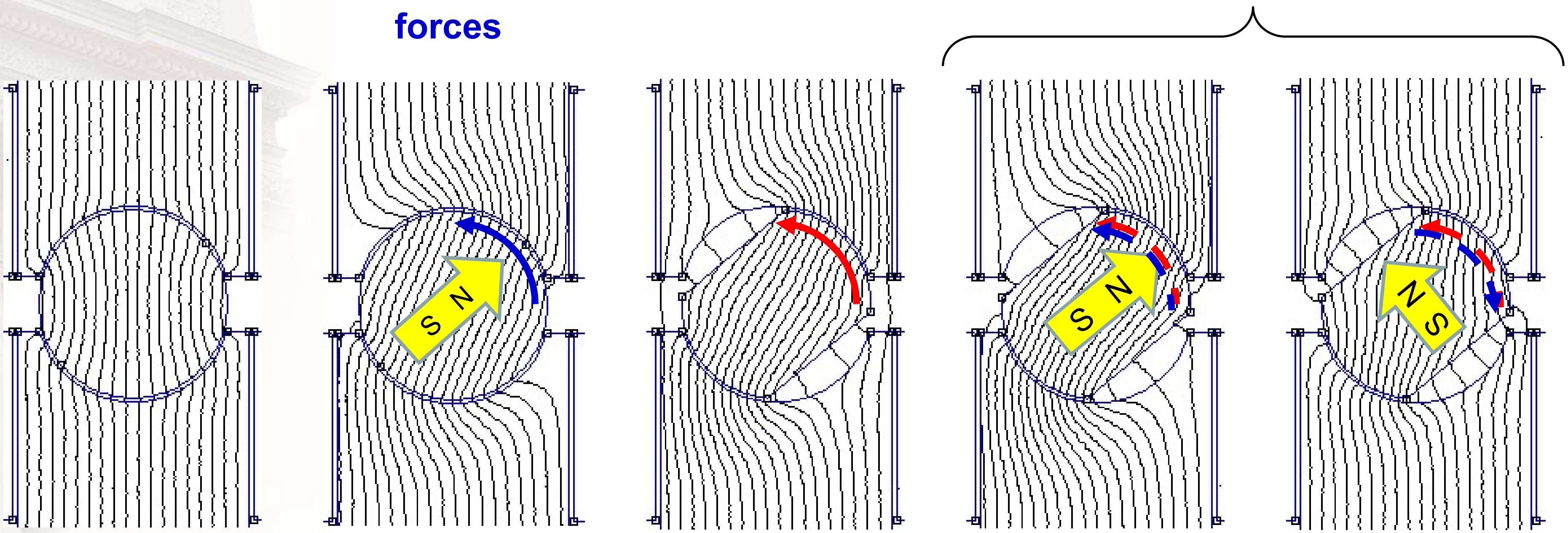
Add the Reluctance torque ...

No Torque

Electrically or permanently magnetized = **Lorenz forces**

Only **Reluctance force**

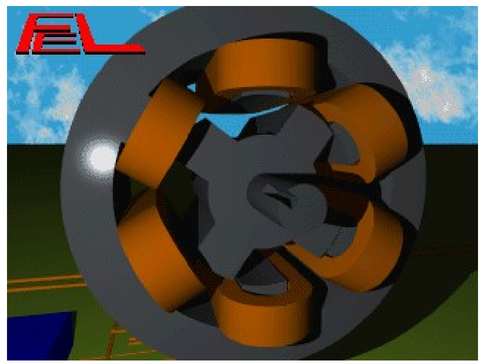
Lorentz AND **Reluctance** forces

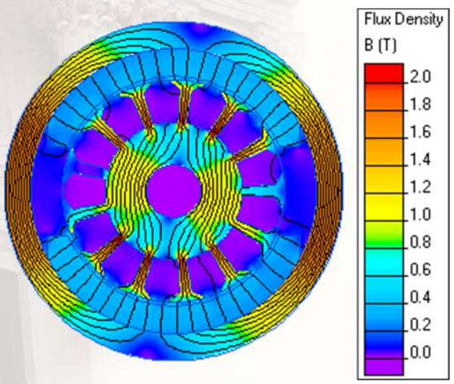


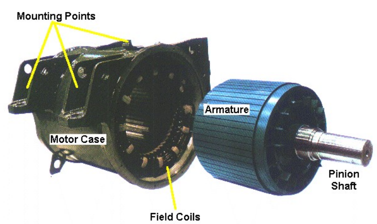
External Magnetic Field

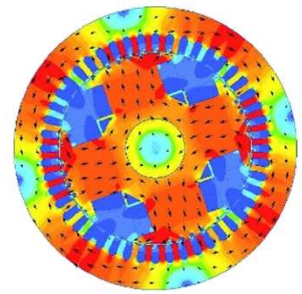
Different mechanical arrangements

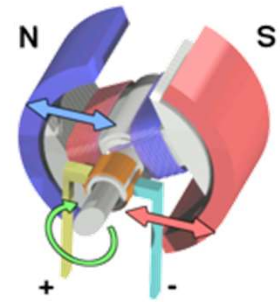
- Windings in the rotor
- Windings in the stator
- Windings in both sides

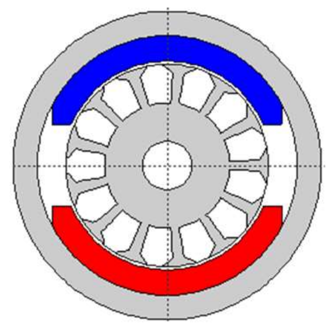


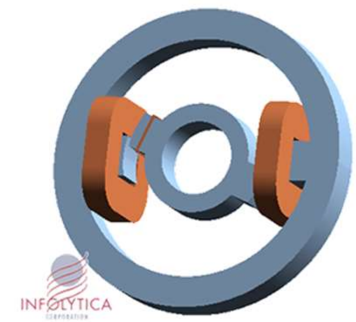


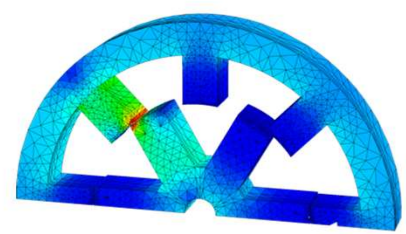




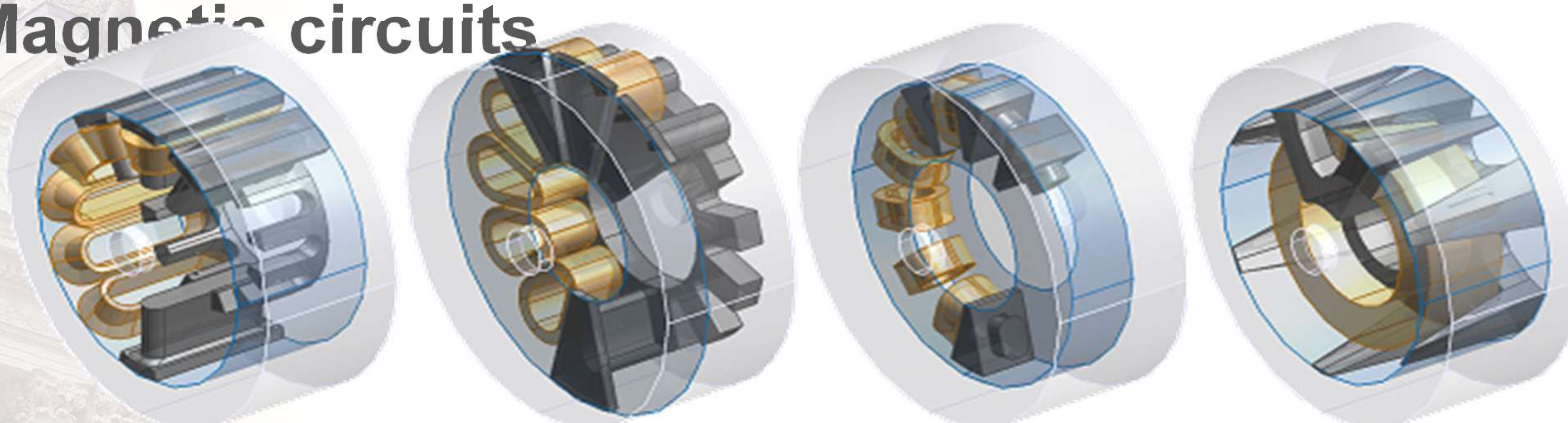








Magnetic circuits



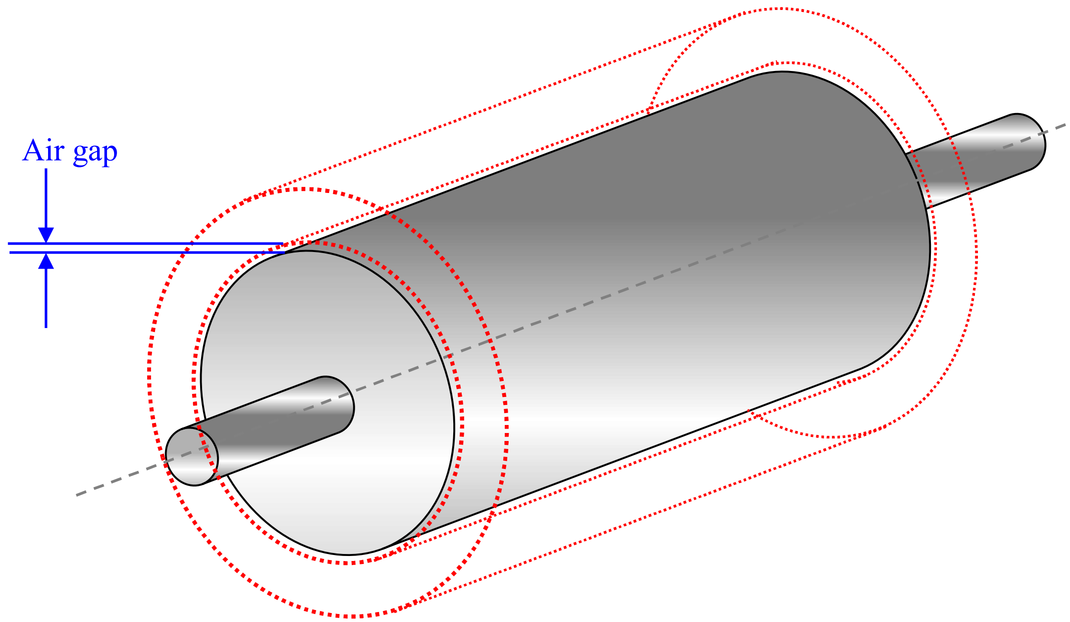
- The **magnetic core** provides mechanic support and construction
- Soft and hard magnetic materials
  - Solid, laminated or powder cores – high μ & B_{sat} vs P_{loss}
  - Discrete, multipole magnets – high B_rH_c vs cost & integration
- Establish magnetic coupling – linkage vs leakage

Electric circuits

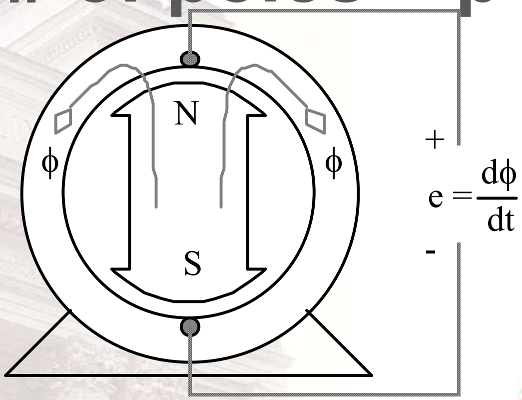
- Initially referred as 3φ symmetric and sinusoidal
- Insulated **electric conductor (Wire) wound as coils** or formed as waves
- Distributed or concentrated windings
  - Arrangement measured by winding factor - ratio of actual MMF to full-pitched winding MMF
- Manufacturability and assembling

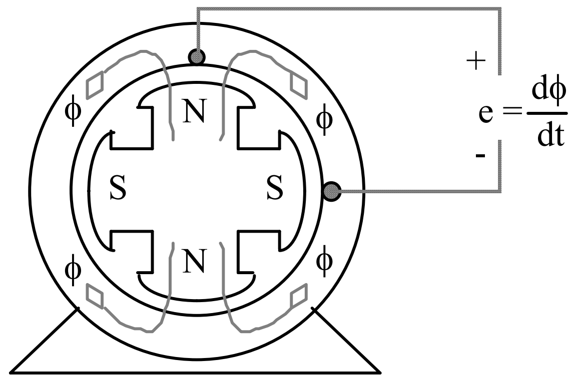
Stator, Rotor and Airgap

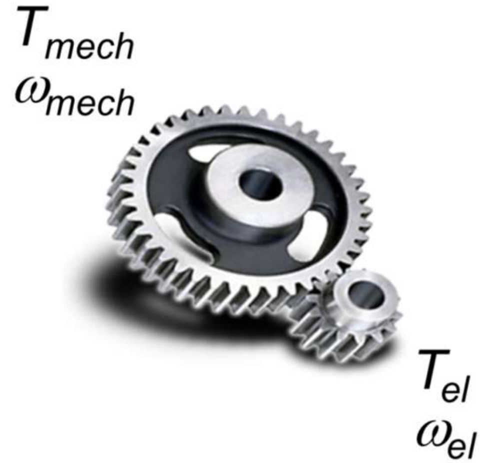
- The **stator** is static (not moving)
- The **rotor** rotates
- The **air gap** seperates them
  - Usually < 1 mm



of poles = p





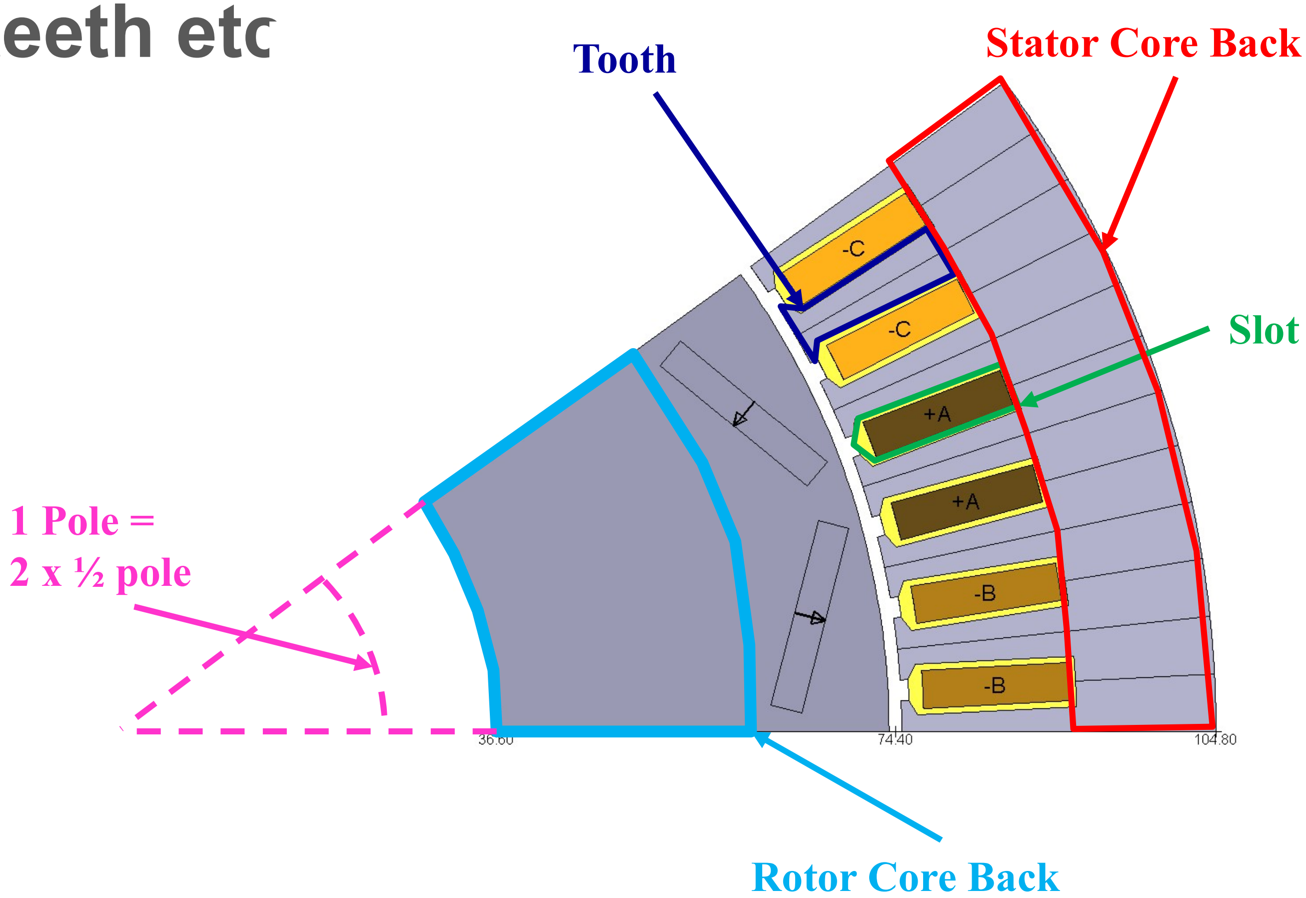


$$\omega_{el} = \frac{p}{2} \cdot \omega_{mech}$$

$$T_{mech} = \frac{p}{2} \cdot T_{el}$$

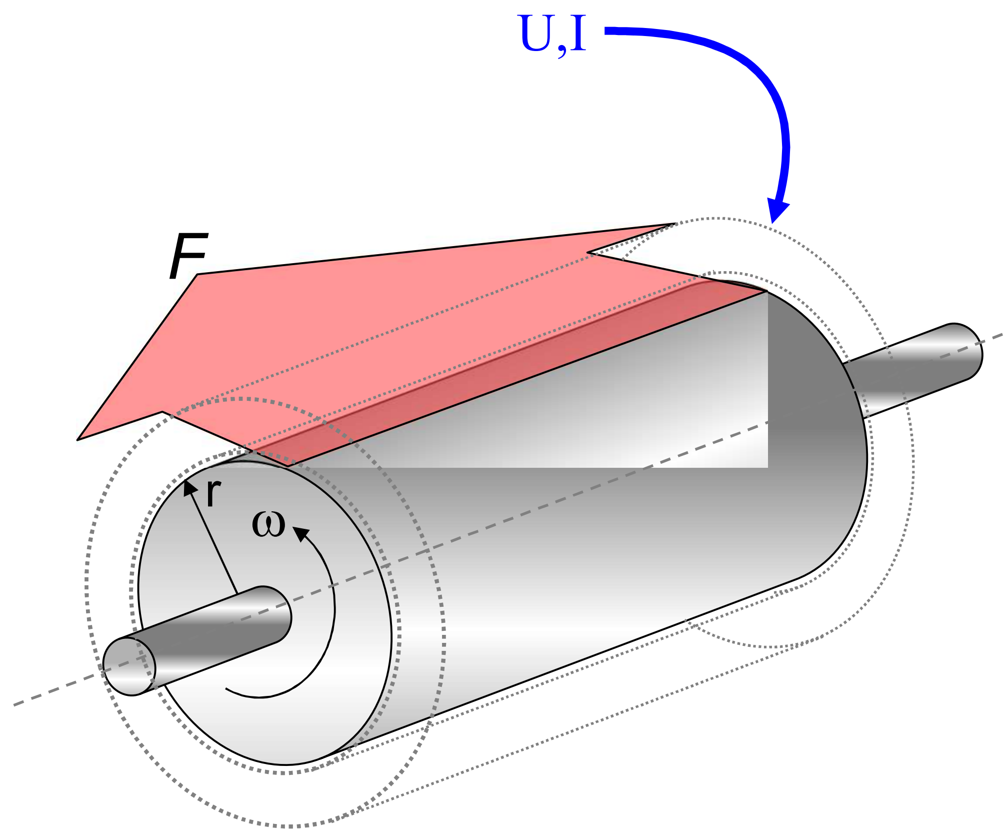
$$\text{Mechanical Power} = \omega_{mech} \cdot T_{mech} = \frac{p}{2} \cdot \omega_{el} \cdot \frac{2}{p} \cdot T_{el} = \omega_{el} \cdot T_{el}$$

Core back, teeth etc



Torque and Power

- Torque = Force * radius
  on the shaft
  T = F * r
- Power = Torque*Speed
  on the shaft
  P = T * ω
  but, also …
- Power = Voltage * Current
  on the electrical terminals
  P = U * I



Tangential force

- Interaction of flux and current
- *"F= B i l "*

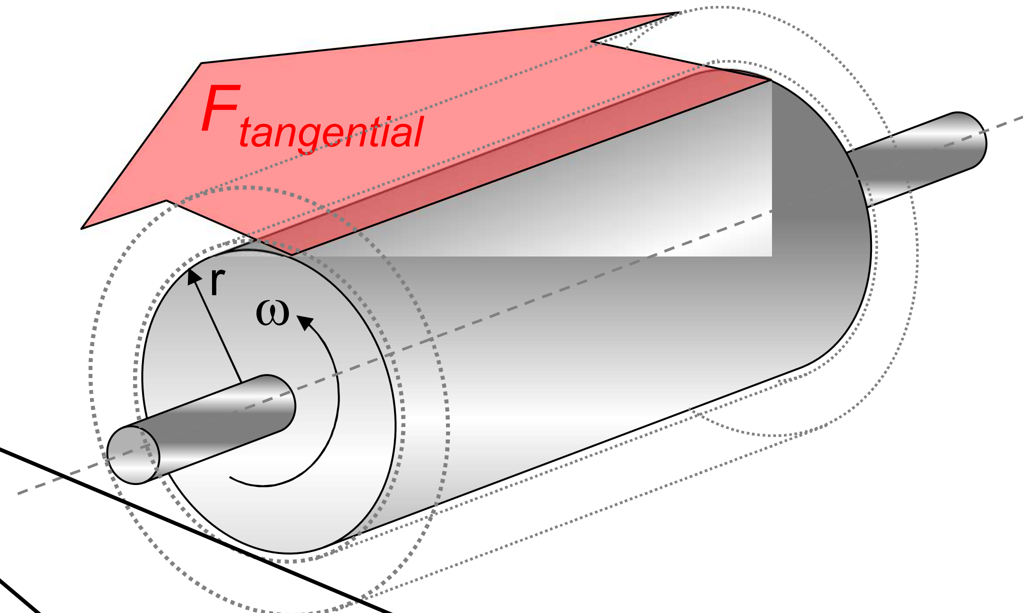
$$F_{tangential} = \frac{\pi}{2} D_{is} l_e B_{gm1} K_{s1}$$

Inner stator diameter

Equivalent active magnetic length

Air gap flux density

Stator Angular Current Density



Stator current / meter air gap periphery

Angular current density

Number of winding turns

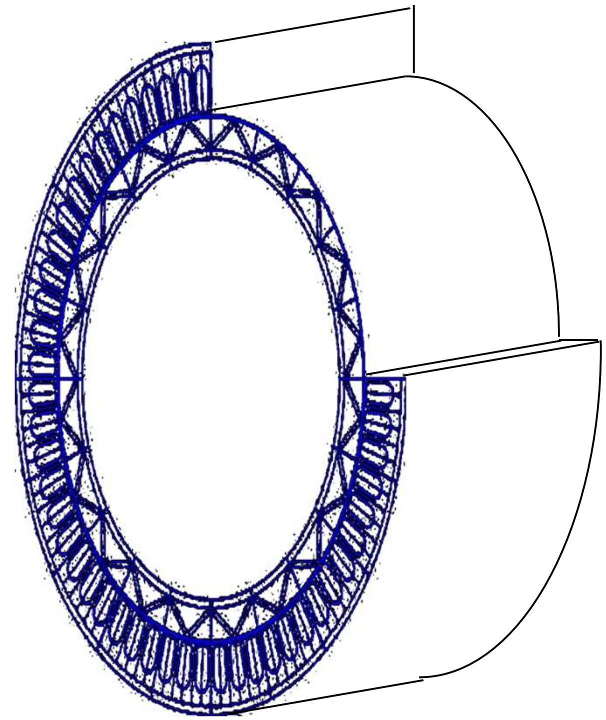
$$K_s(\theta) = \frac{6}{\pi} \cdot \frac{k_1 N_s}{D_{is}} \cdot \hat{i}_s \cdot \cos\left(\frac{p\theta}{2} - \omega_e t\right) \quad [A/m]$$

Winding factor

Number of poles

Phase current amplitude

Stator inner diameter

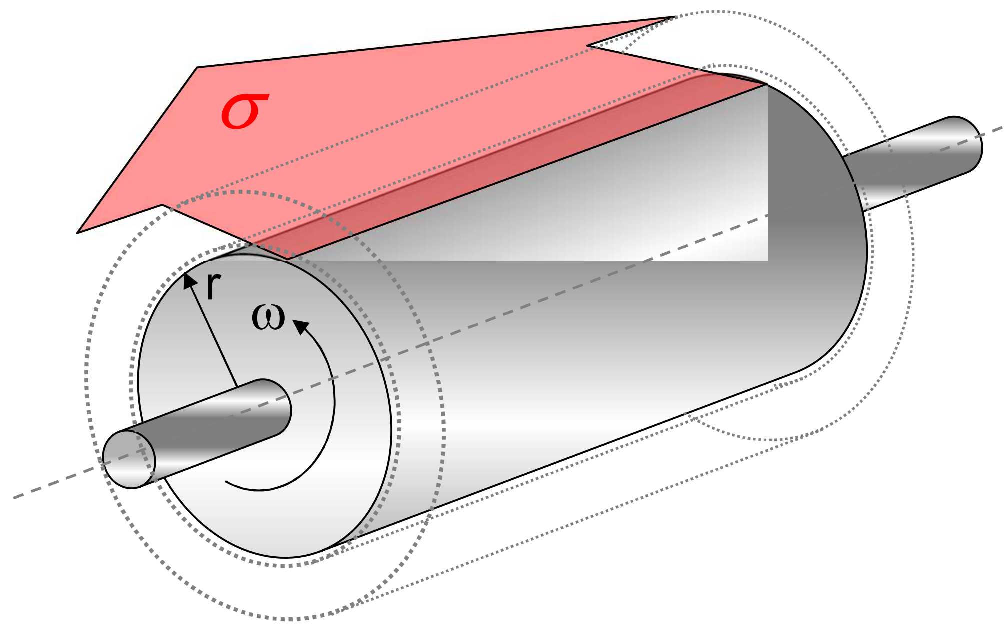


Shear Force & Torque

- Current and Flux interact for tangential force
  σ = Force/Unit area is a key figure
- A good design accomplish about
  σ = 10 000 … 30 000 [N/m^2]
- … in continuous operation and
  2…4 times that in transient operation

$$\sigma = \left(\frac{F}{A}\right)_{avg} = \frac{\frac{\pi}{2} D_{is} l_e B_{gm1} K_{s1}}{\pi D_{is} l_e} = \frac{B_{gm1} K_{s1}}{2} \quad [N/m^2]$$

$$T = \frac{\pi}{4} D_{is}^2 l_e \cdot B_{gm1} K_{s1}$$



Conclusion on torque

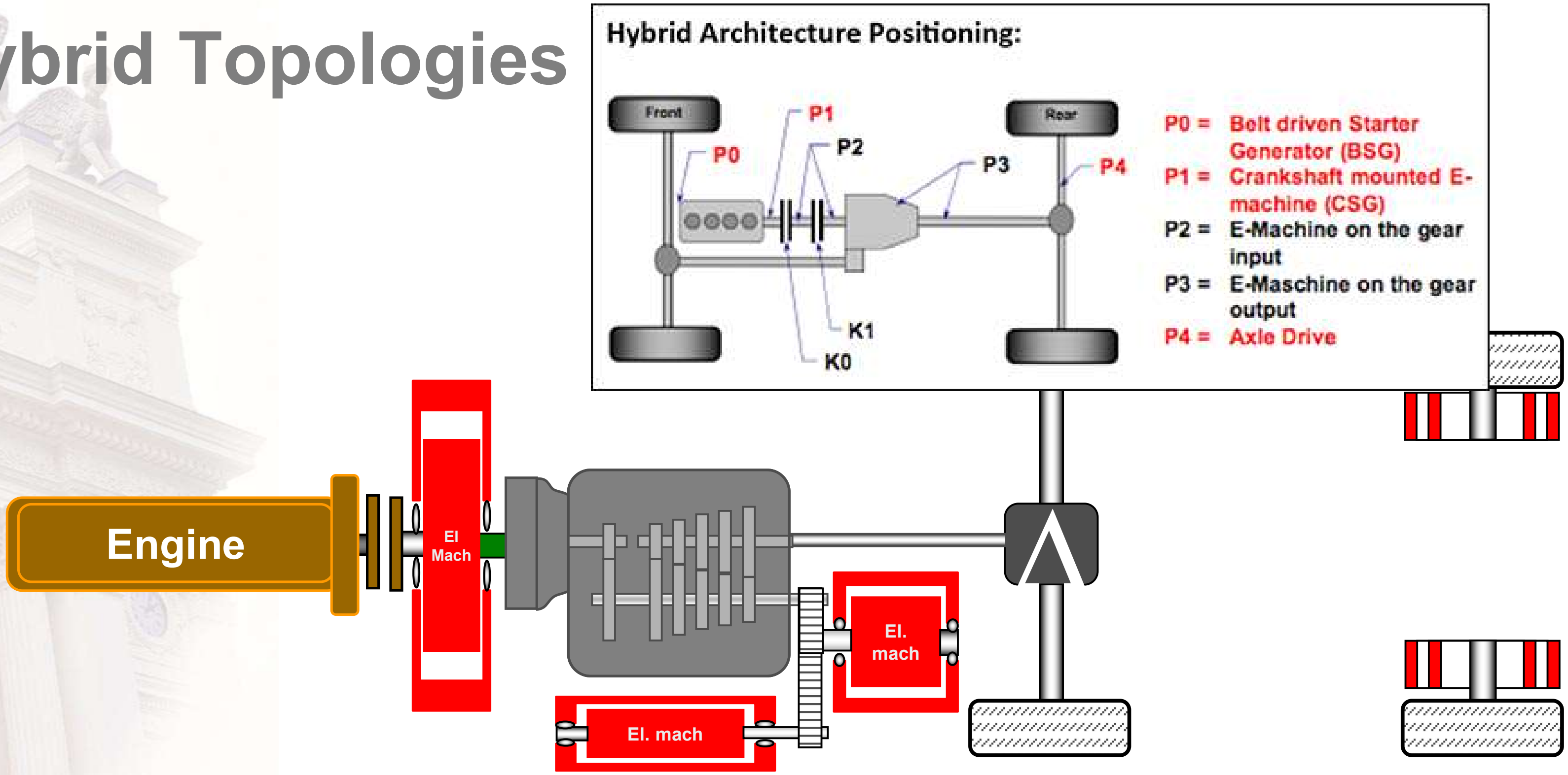
The torque is proportional to the:

- Magnetic flux density – Limited by material propertied to about 1.0 ... 1.5 Tesla
- Spatial current ”density” – Limited by cooling capability
- Axial length of the machine
- Diameter SQUARED !

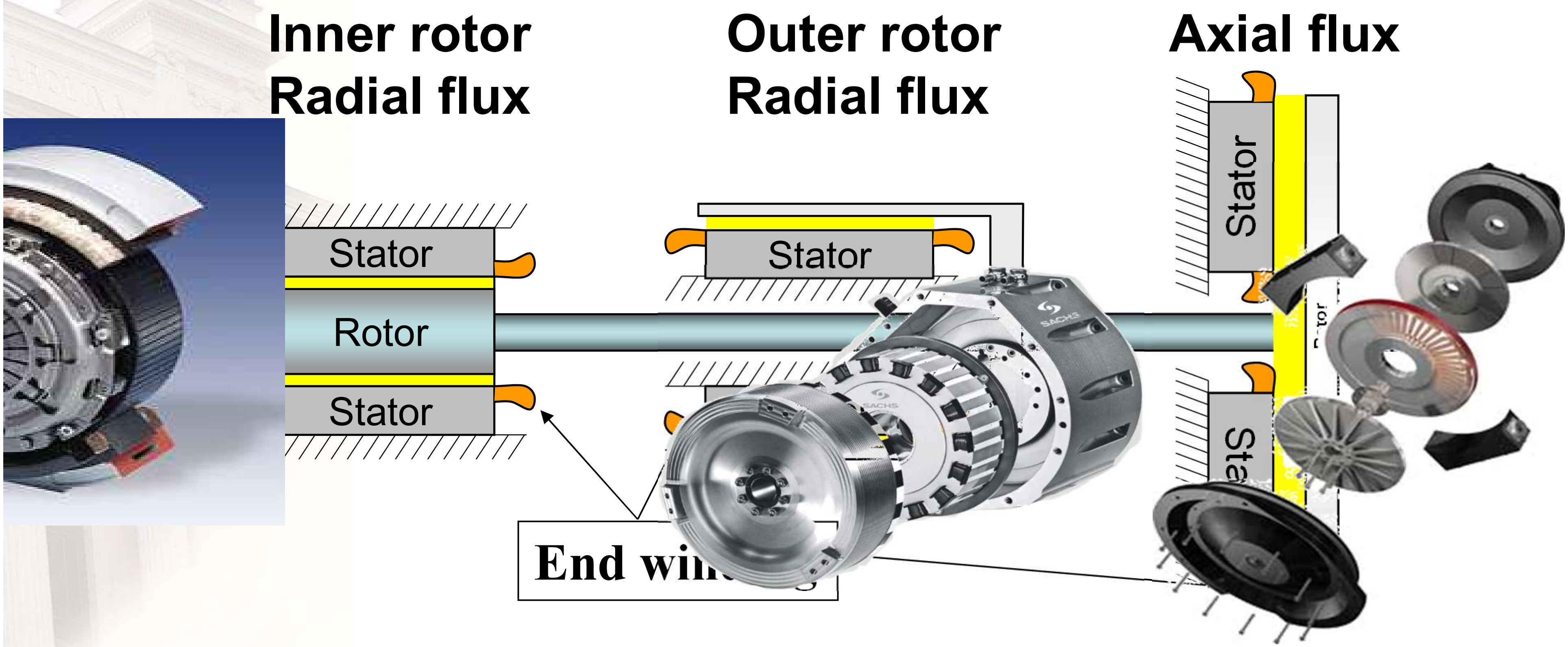
(Axial length and diameter squared) = Rotor Volume

$$T = \frac{\pi}{4} D_{is}^2 l_e \cdot B_{gm1} K_{s1}$$

Hybrid Topologies



Inner or Outer Rotor, Radial or Axial flux …



Distributed or Concentrated winding

Axially shorter end winding
Cheaper assembly
Lower torque quality

Longer end winding
More expensive assembly
Higher torque quality

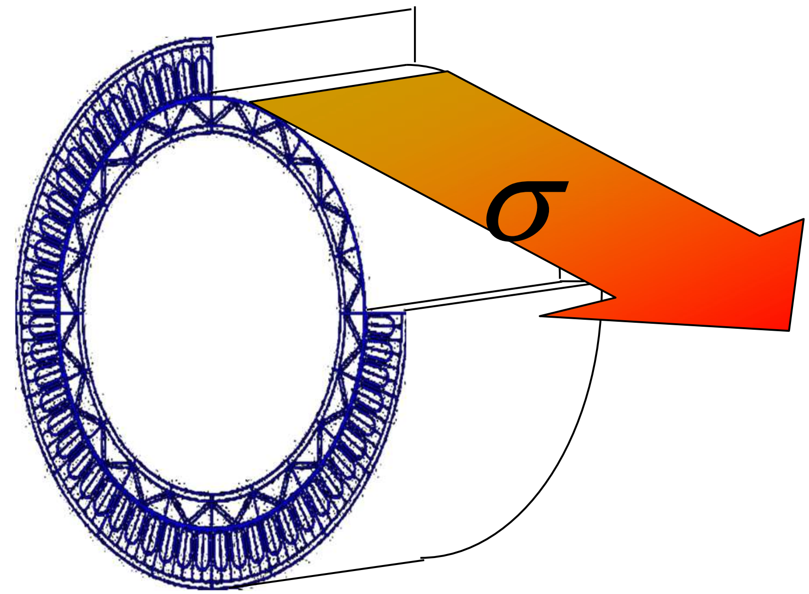
Shear Force & Torque

Current and Flux interact for tangential force

σ = Force/Unit area is a key figure

A good design accomplish

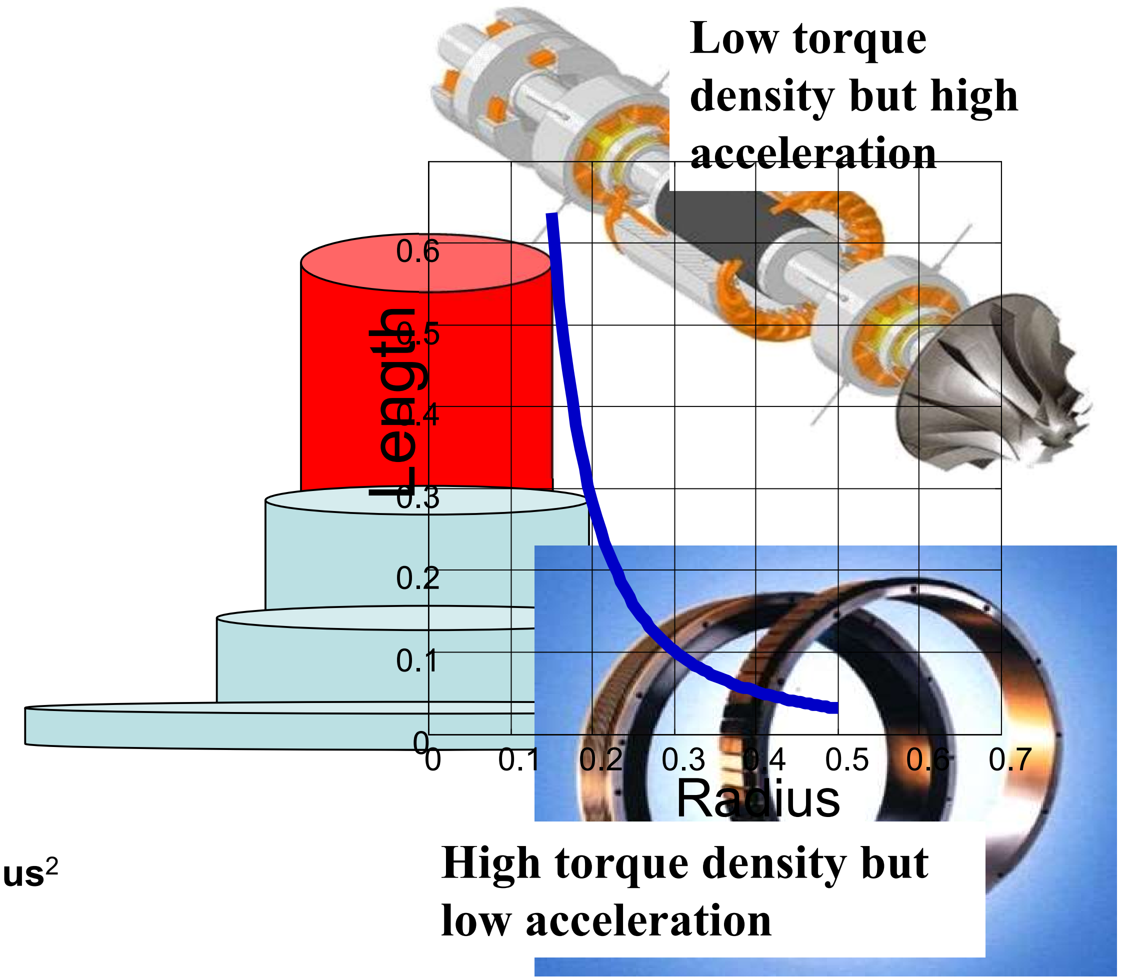
about σ = 10000-30000 [N/m^2] in continuous operation and 2..4 times more in transient operation



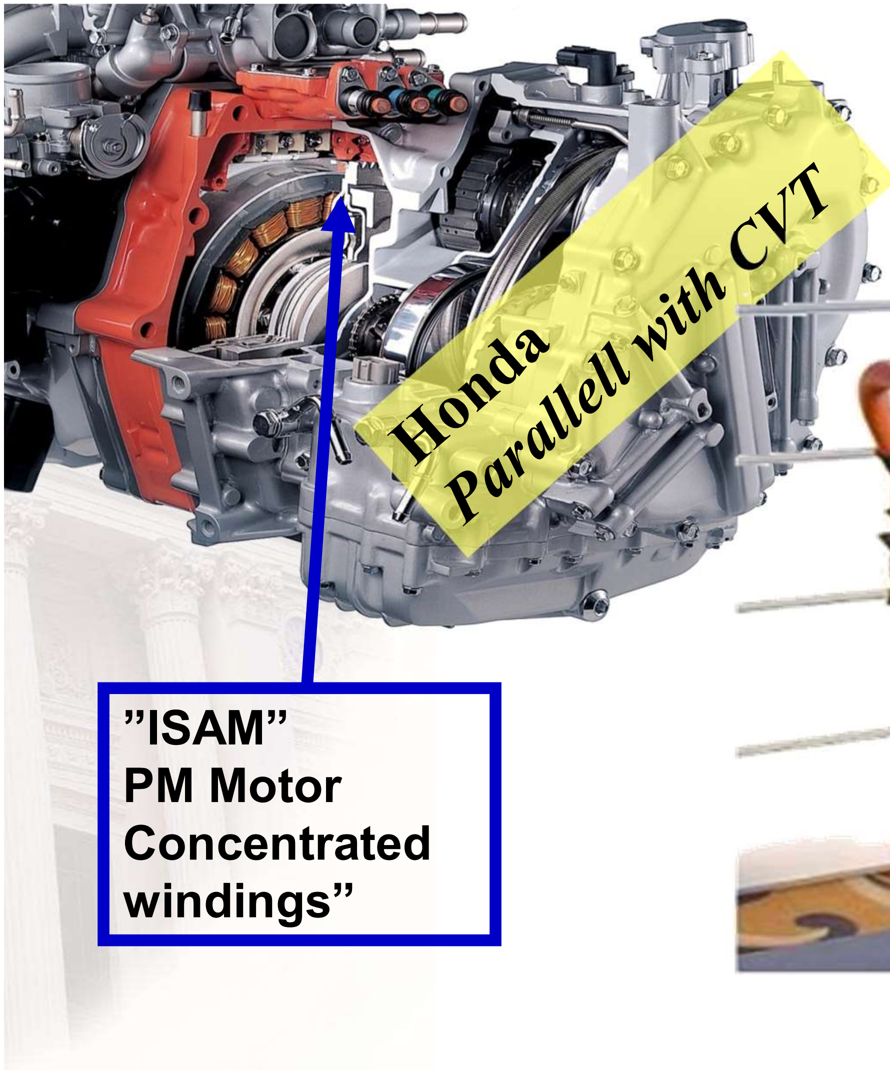
Form Factor

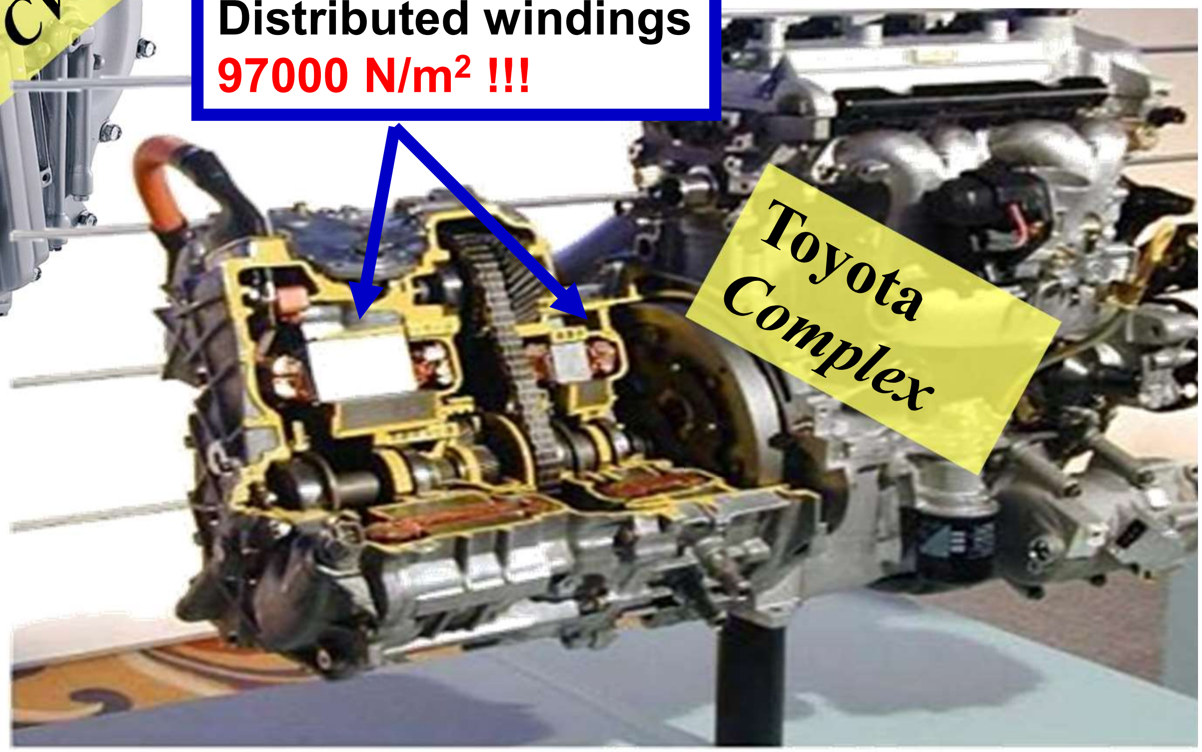
- For the same torque, a machine can be either short and wide, or long and slender …
- Assume 25000 [N/m^2], and a desired torque of 1000 Nm, AND that the stator outer radius is 0.15 – 0.5 meter.
  - How long will the machine be to fulfill the torque requirement?

- **The long and slender machine will accelerate faster**
  - **Torque ~ radius^2*length**
  - **Inertia ~ radius^4*length**
- **Acceleration = Torque/Inertia ~ 1/radius^2**

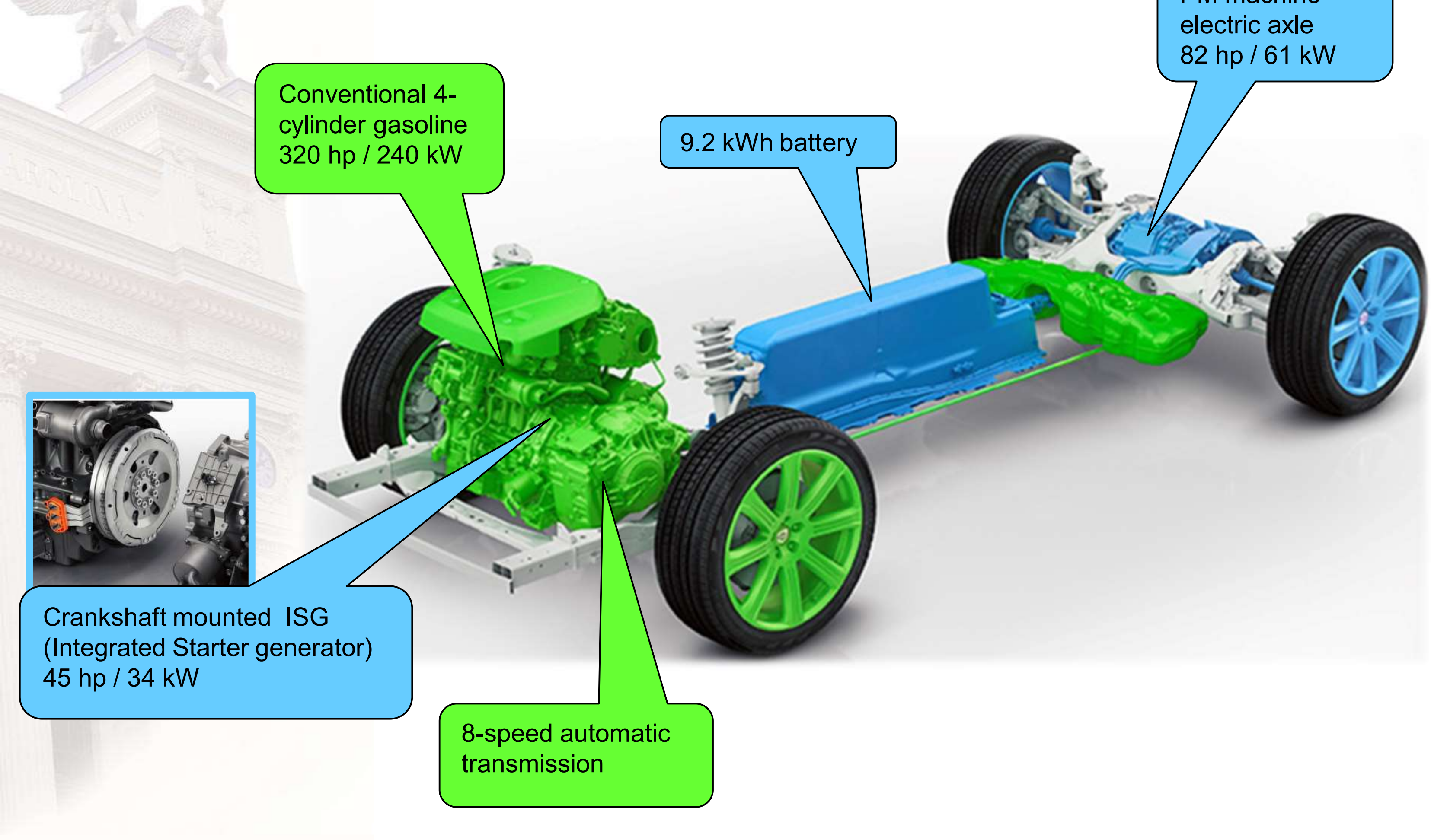


Honda and Toyota



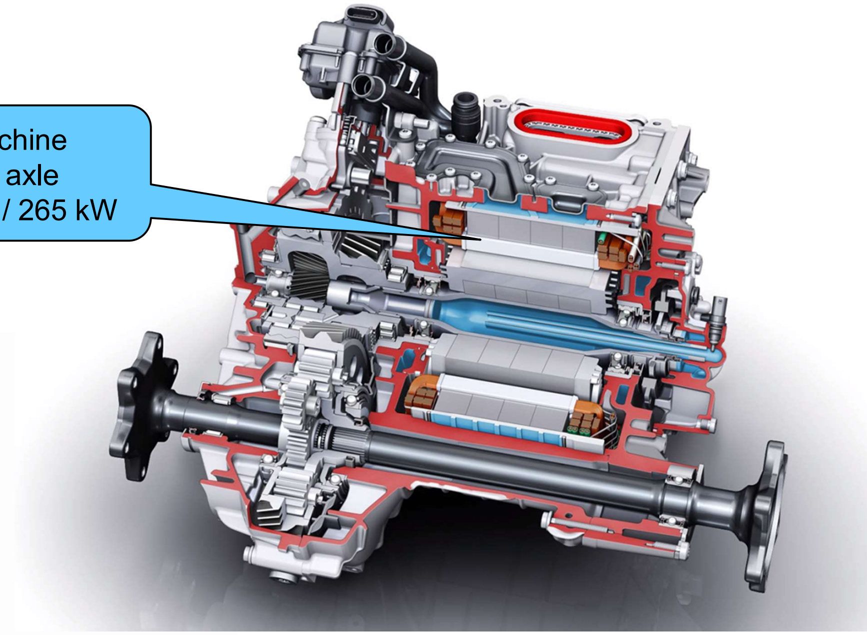


Volvo V90 T8

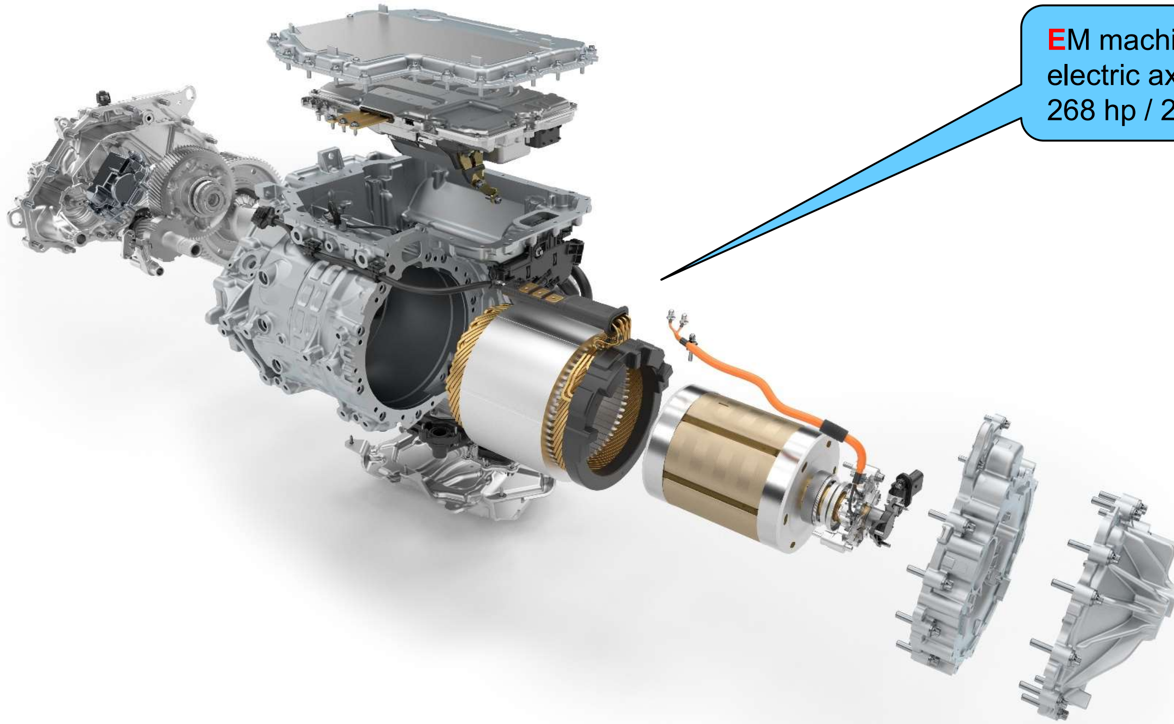


Conventional 4-cylinder gasoline 320 hp / 240 kW
9.2 kWh battery
PM machine electric axle 82 hp / 61 kW
Crankshaft mounted ISG (Integrated Starter generator) 45 hp / 34 kW
8-speed automatic transmission

Audi e-tron (full electric)



BMW iX3 drive train



EM machine
electric axle
268 hp / 200 kW

Conclusions on force and movement

- *The same generic circuit accomplish both linear and rotating movement.*

- *One phase is not enough for continuos force*

- *Qualitative:*

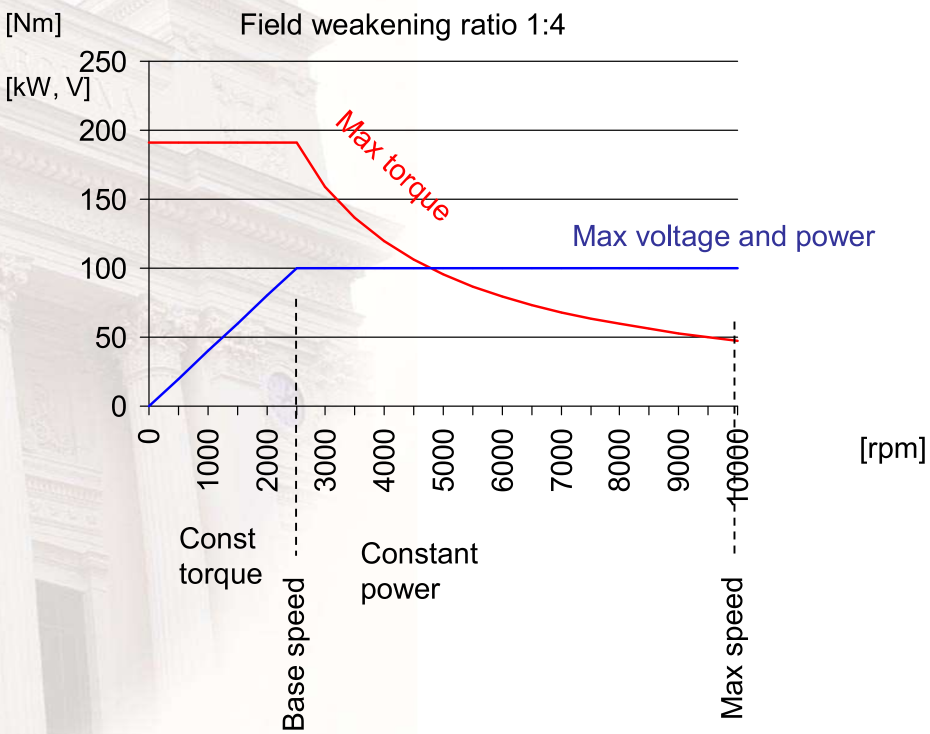
  - *Voltage ~ Speed*
  - *Current ~ Force*

Field Weakening : I

- Remember:
  - Voltage ~ flux density * speed
  - Torque ~ flux density * current
  - Power ~ speed*torque = voltage*current

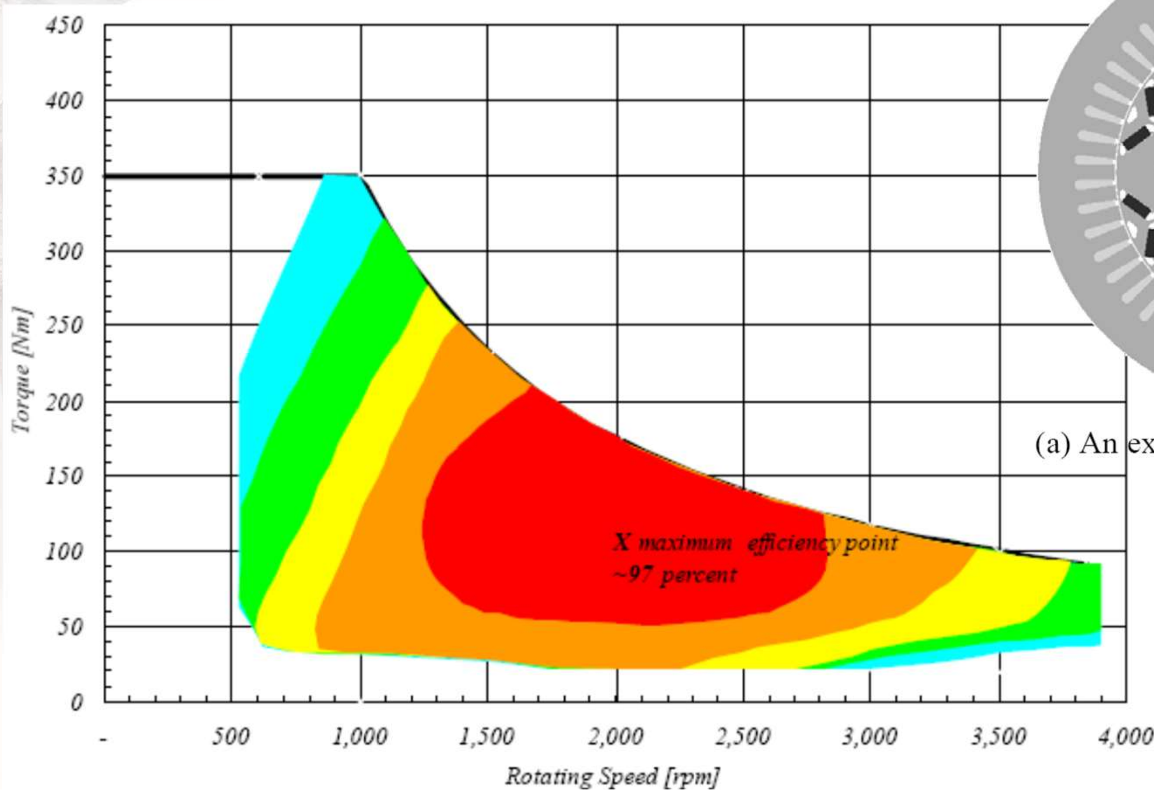
- The required voltage ”hits the roof” at some speed. What to do, to increase speed beyond?
  - Answer: Reduce flux density’
  - Consequences:
    - *The voltage requirement is kept constant, as desired*
    - *The torque capability drops as the flux density.*
    - *The power is kept constant, since the speed increases in the same rate as the torque drops with increasing speed.*

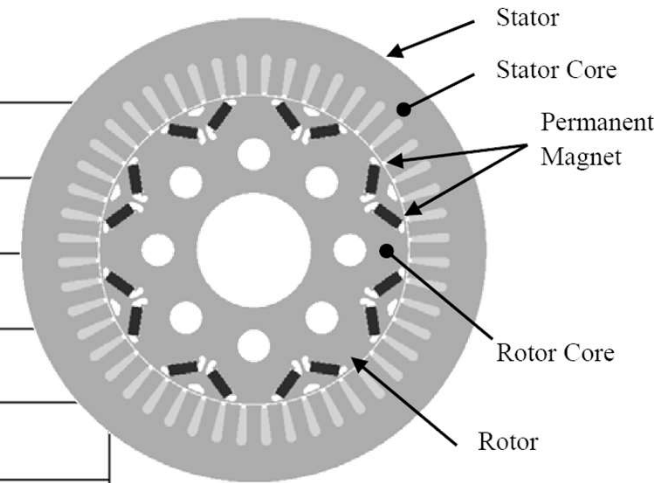
Field Weakening : II



Example from Toshiba

"Large Torque and High Efficiency Permanent Magnet Reluctance Motor for A Hybrid Truck" - Masanori Arata et. Al, EVS-22



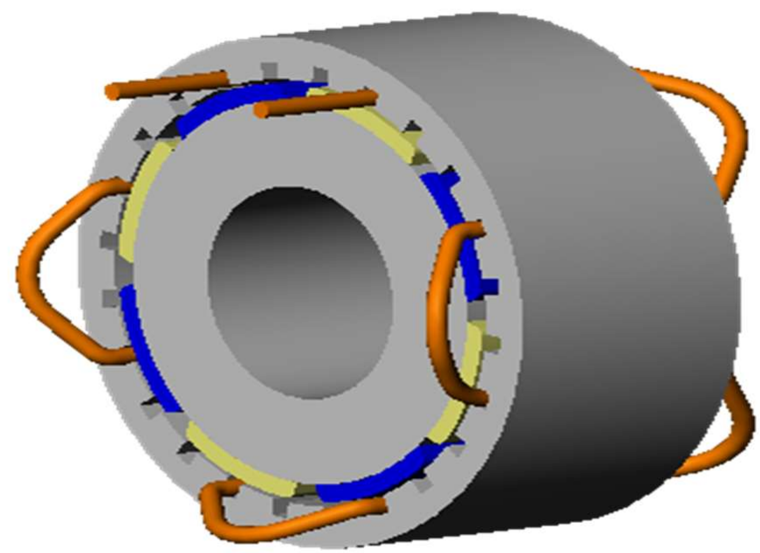


(a) An example of cross section of the PRM

Permanent Magnet Synchronous Machines

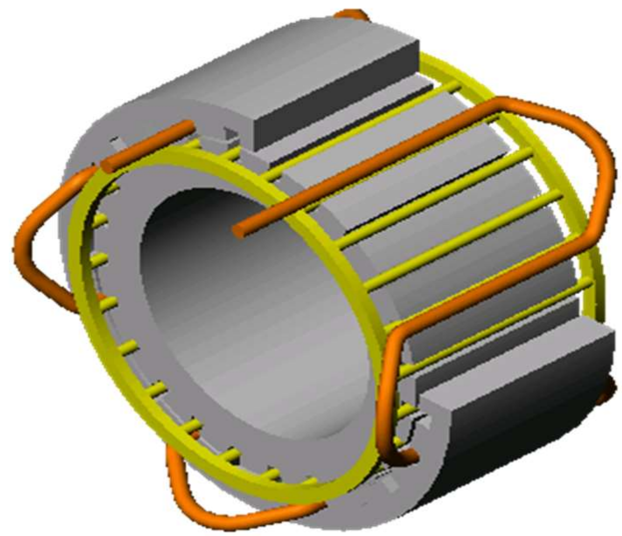
- Same as the generic machine
- Voltage and frequency proportional to speed
- Current proportional to torque

- High torque density
  - 1...10 Nm/kg
  - Compare to ICE 1...2 Nm/kg
- High efficiency
  - Up to 97%
- Higher efficiency, higher torque density and more expensive than other machines
  - Due to the permanent magnets.

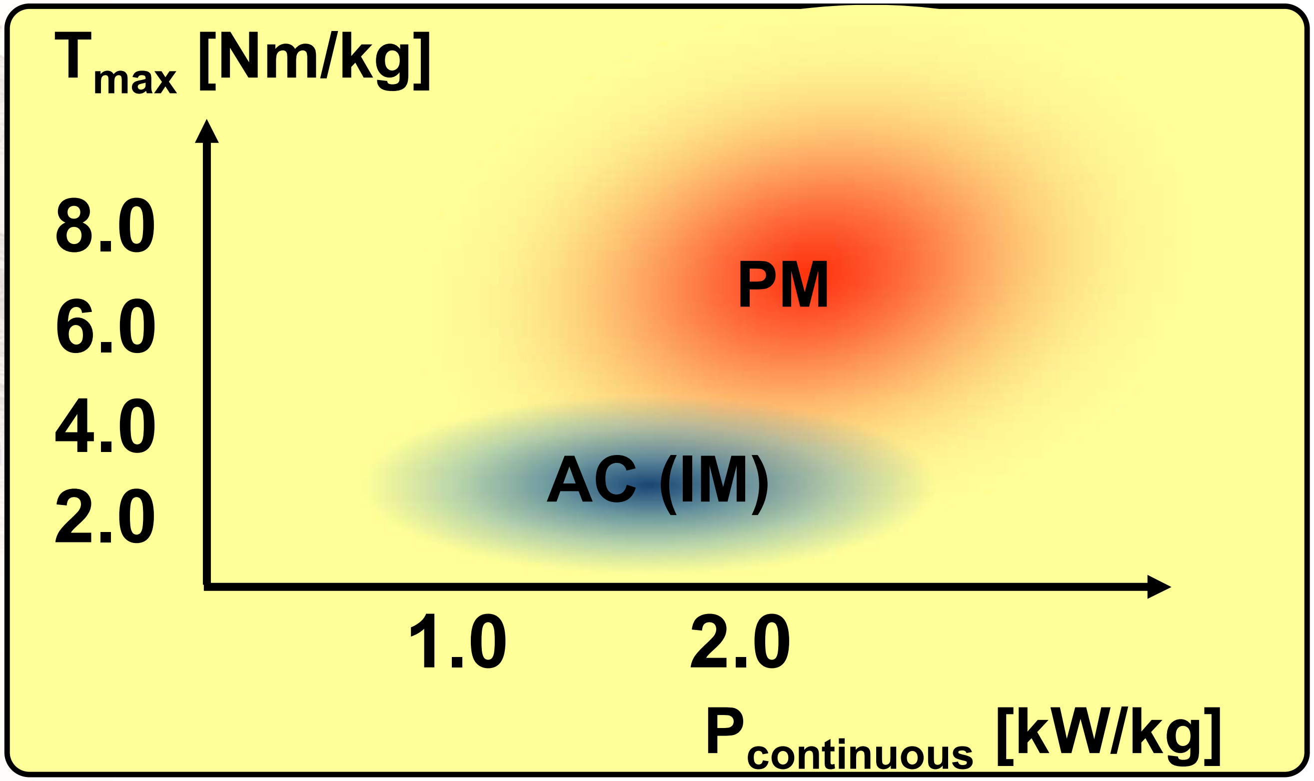


The Induction Machine : I

- Same stator as the PMSM
- The rotor is a short circuited ”cage”
- The rotor current must be induced magnetically
  - Losses related to magnetization ”competes” with losses due to torque generation.
- Robust construction
- Low cost
- Low/no maintenance
- Heavily standardized for industrial applications
- Voltage and frequency proportional to speed, like PMSM



Comparison – Electric Drives

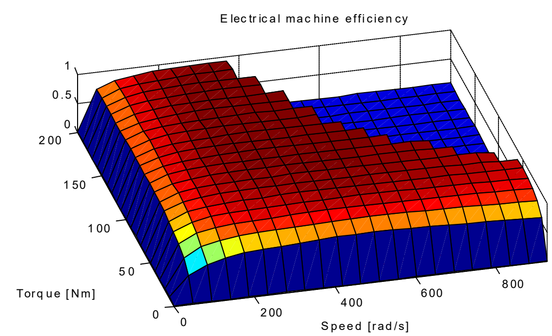


Electrical machine losses

Hysteresis losses

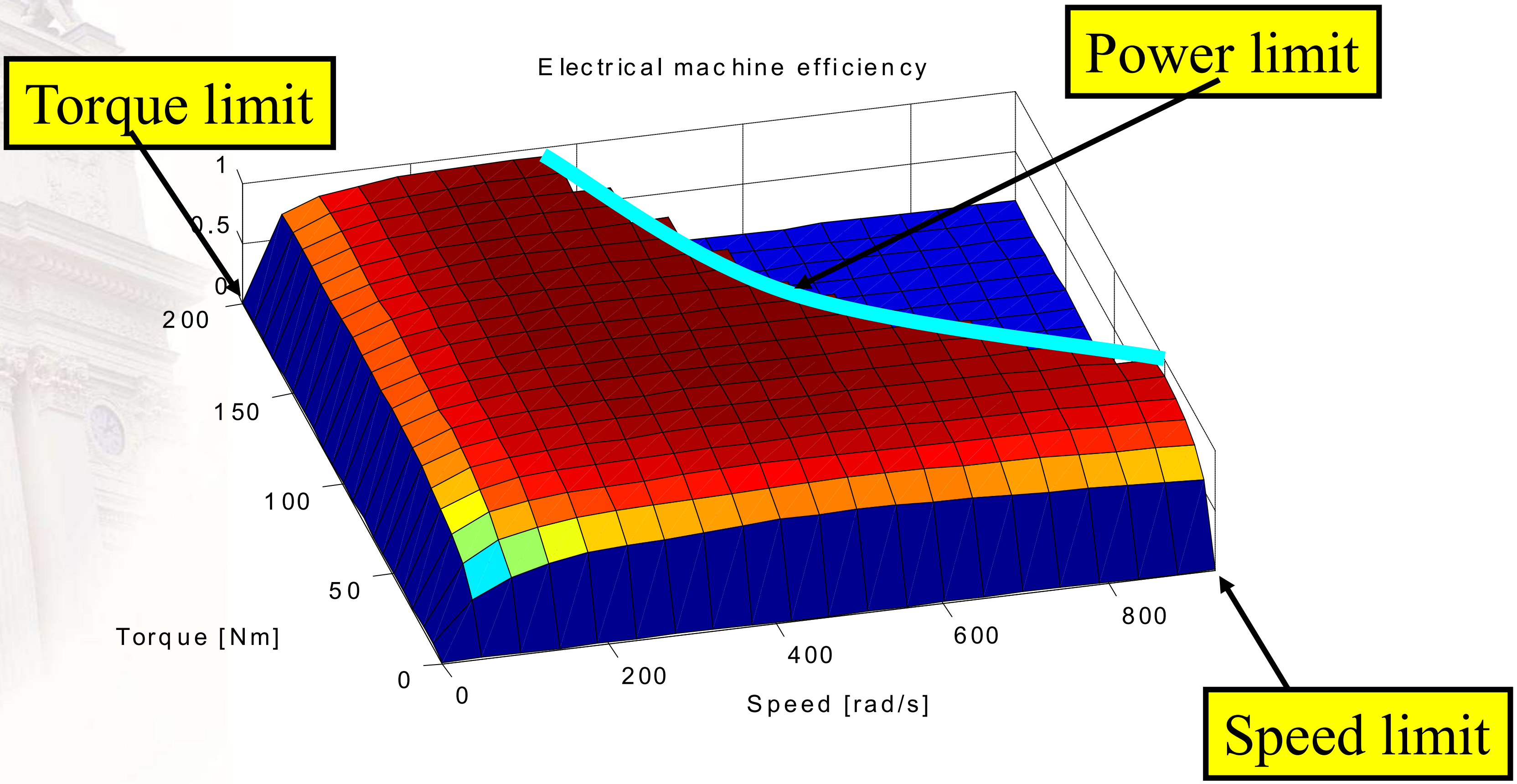
Eddy current losses

- Several types:
  - Copper losses (Ri^2)
  - Iron losses $(k_1 * f * B^2 + k_2 * (f * B)^2)$
  - Windage losses (surface speed)
  - Other friction losses



- Approximately calculated by
  - [EtaEM,Tem,Wem] = CreateEMmap(Pem_max,wem_max,Tem_max)

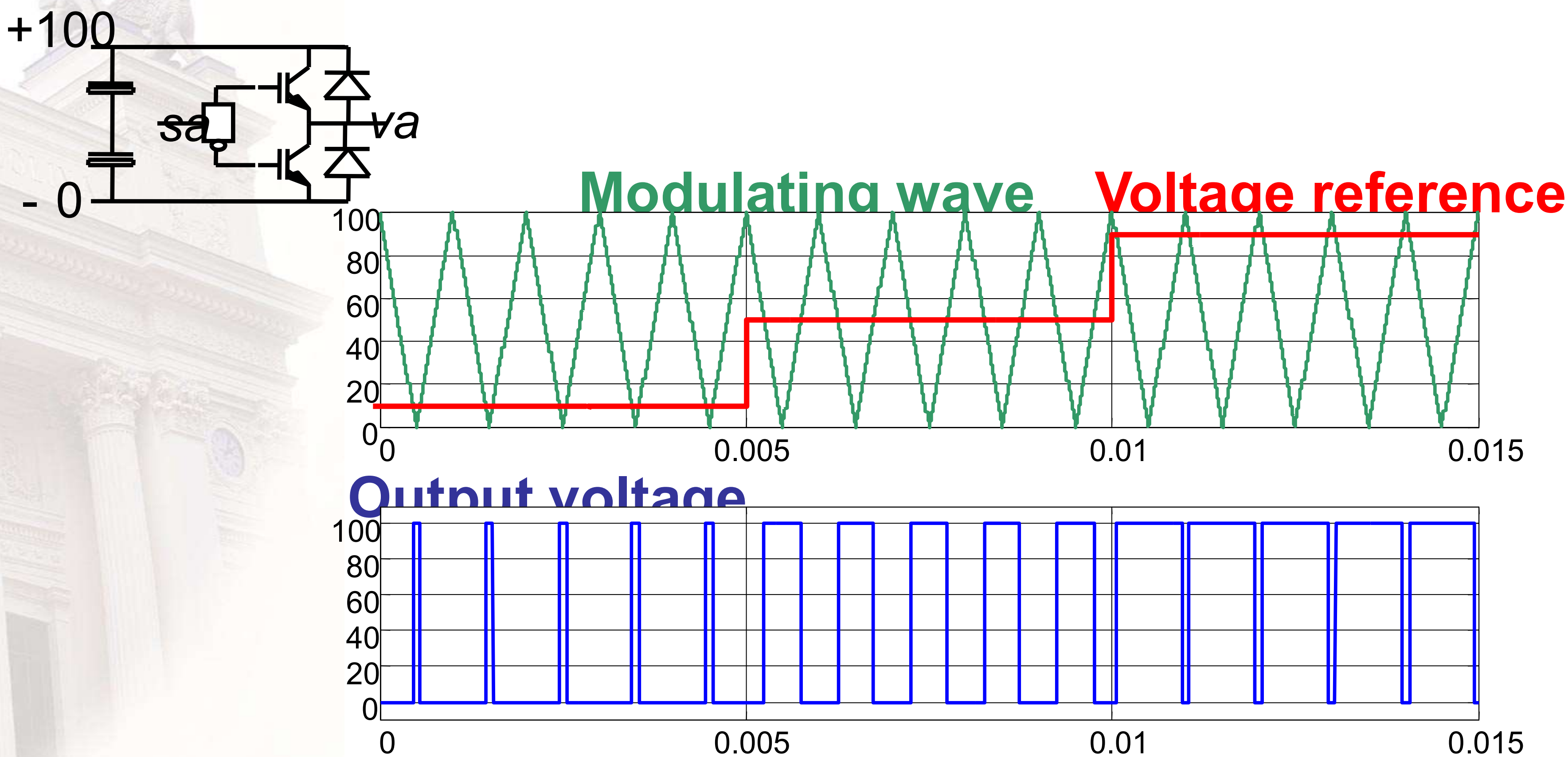
The Traction motor efficiency



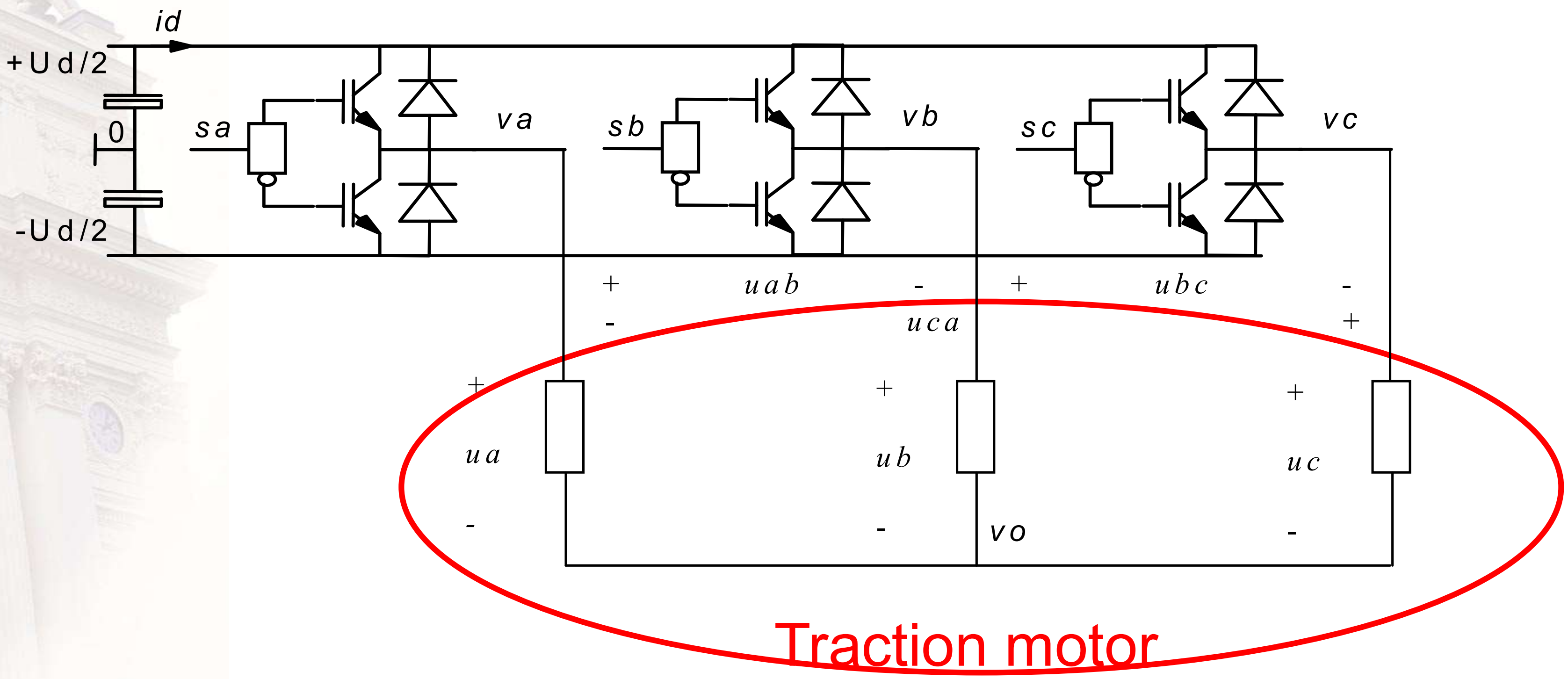
Power Electronics

- Needed to condition the battery voltage to the different electrical drives
- Use switching technology for high efficiency
  - Conventional converters (like loudspeaker amplifiers) efficiency 25-60 % due to continuous control of the voltage.
  - Switching means “on/off” control of voltage, leading to efficiency above 95 %.

1 Phase Pulse Width Modulation (PWM)

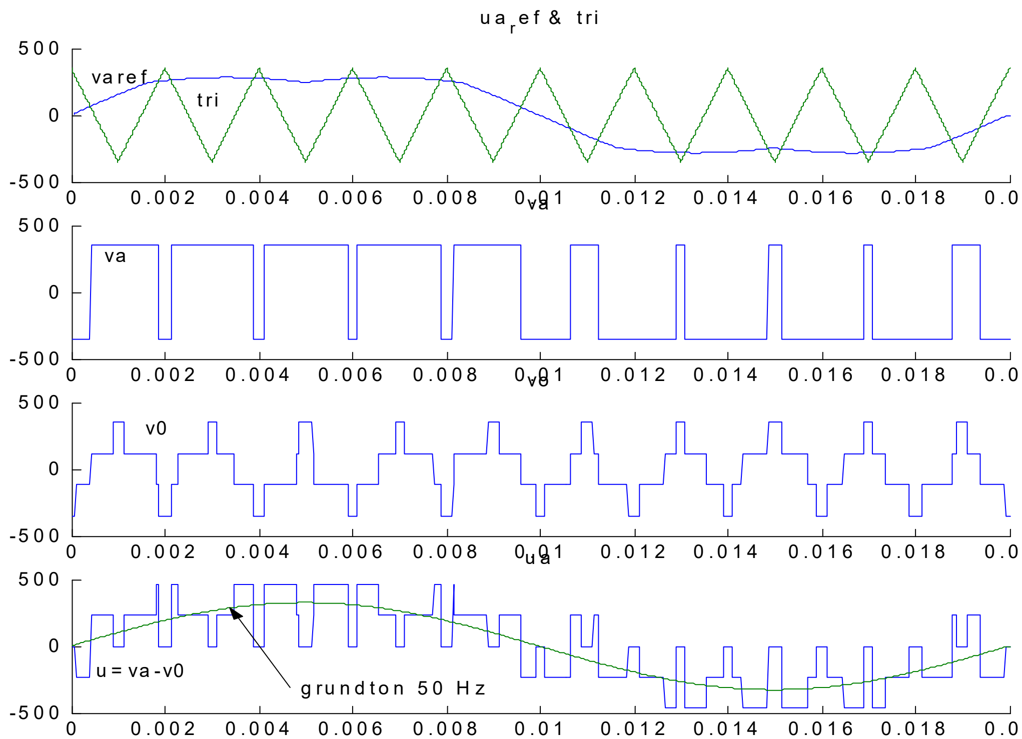


Three-phase Converters

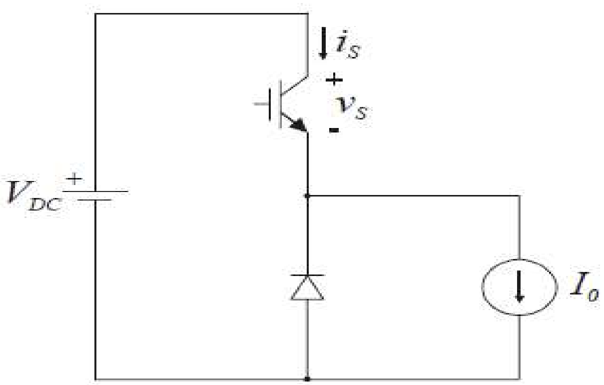


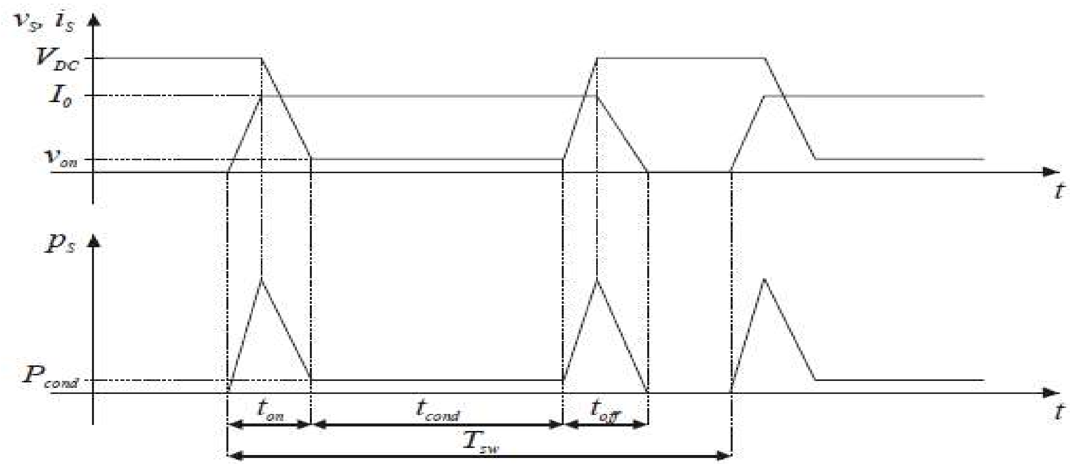
Three-phase Pulse Width Modulation

- The voltages contain high harmonics that cause:
  - Audible noise
  - Torque ripple
  - EMC problems



Simple Converter Loss Model





$$p_S(t) = v_S(t) \cdot i_S(t)$$

Switching and Conduction losses

Energy losses: $E_S(T_{sw}) = \int_{T_{sw}} p_S(\tau)d\tau = E_{S,on}(T_{sw}) + E_{S,cond}(T_{sw}) + E_{S,off}(T_{sw})$

$$E_{S,on}(T_{sw}) = \int_{t_{on}} p_S(\tau)d\tau = V_{DC}\cdot I_0 \cdot \frac{t_{on}}{2}$$

$$E_{S,cond}(T_{sw}) = \int_{t_{cond}} p_S(\tau)d\tau = V_{S(on)}\cdot I_0 \cdot t_{cond}$$

Note $V_{S(on)} = V_{S0} + R_S \cdot I_0$

$$E_{S,off}(T_{sw}) = \int_{t_{off}} p_S(\tau)d\tau = V_{DC}\cdot I_0 \cdot \frac{t_{off}}{2}$$

Power losses: $P_S(T_{sw}) = \frac{E_S(T_{sw})}{T_{sw}} = P_{S,on}(T_{sw}) + P_{S,cond}(T_{sw}) + P_{S,off}(T_{sw})$

$$P_{S,on}(T_{sw}) = \frac{E_{S,on}(T_{sw})}{T_{sw}} = E_{S,on}(T_{sw})\cdot f_{sw} = \frac{V_{DC}\cdot I_0 \cdot t_{on}}{2}\cdot f_{sw}$$

$$P_{S,cond}(T_{sw}) = \frac{E_{S,cond}(T_{sw})}{T_{sw}} = V_{S(on)}\cdot I_0 \cdot \frac{t_{cond}}{T_{sw}} = V_{S(on)}\cdot I_0 \cdot D_S$$

$$P_{S,off}(T_{sw}) = \frac{E_{S,off}(T_{sw})}{T_{sw}} = E_{S,off}(T_{sw})\cdot f_{sw} = \frac{V_{DC}\cdot I_0 \cdot t_{off}}{2}\cdot f_{sw}$$

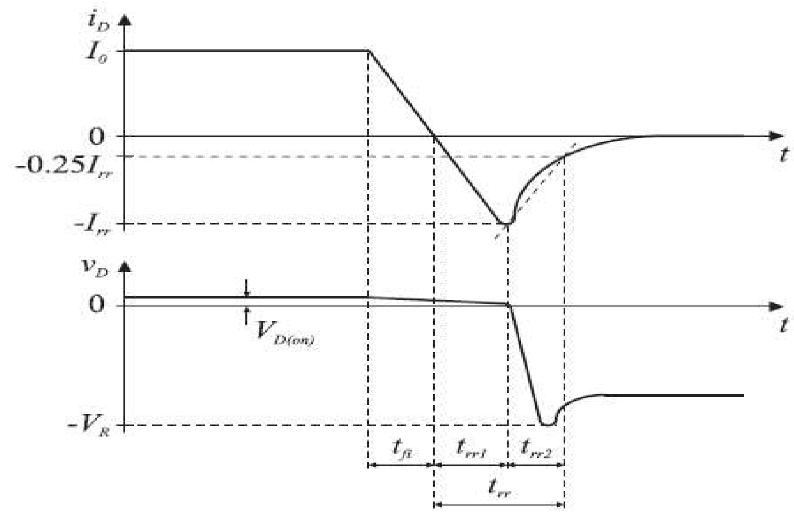
$$P_{S,sw}(T_{sw}) = P_{S,on}(T_{sw}) + P_{S,off}(T_{sw})$$

Reverse recovery Losses

If specified, use:

$$E_{S,on}(T_{sw})=\frac{E_{on,n}}{V_{DC,n}\cdot I_{0,n}}\cdot V_{DC}\cdot I_0$$

$$E_{S,off}(T_{sw})=\frac{E_{off,n}}{V_{DC,n}\cdot I_{0,n}}\cdot V_{DC}\cdot I_0$$



For the freewheeling diode:

$$P_{D,cond}(T_{sw})=V_{D(on)}\cdot I_0\cdot D_D \qquad V_{D(on)}=V_{D0}+R_D\cdot I_0$$

$$D_D\approx 1-D_S$$

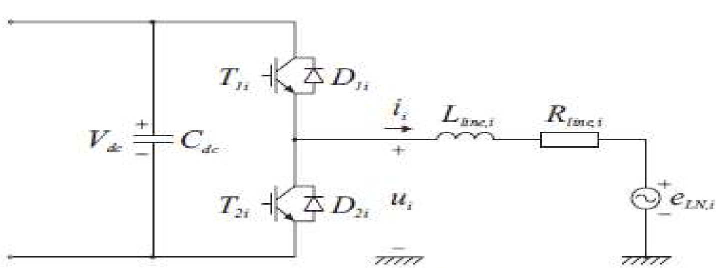
$$P_{D,rr}=V_{DC}\cdot Q_f\cdot f_{sw} \qquad Q_f\approx\frac{1}{S+1}\cdot Q_{rr} \text{ where } S=\frac{t_{rr1}}{t_{rr2}}$$

Fig

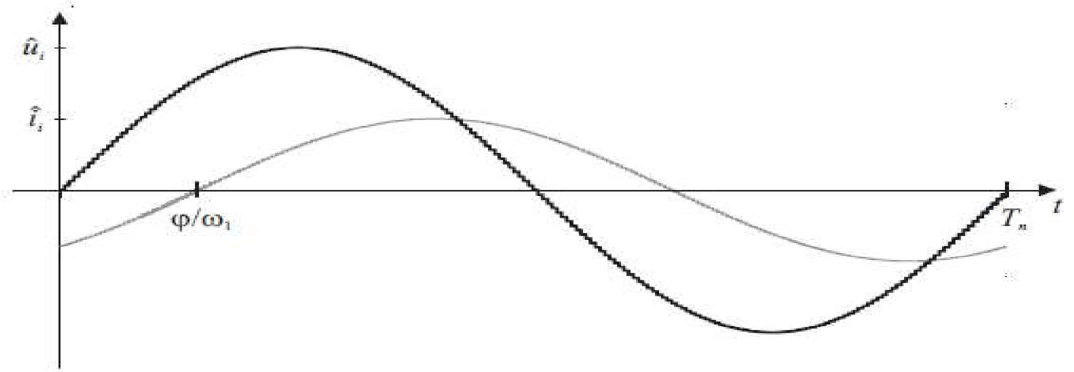
If specified, use:

$$P_{D,off}=E_{D,off}(T_{sw})\cdot f_{sw}\ ,\ E_{D,off}(T_{sw})=\frac{E_{off,n}}{V_{DC,n}\cdot I_{0,n}}\cdot V_{DC}\cdot I_0 \qquad Q_f=\frac{Q_{f,n}}{I_{0,n}}\cdot I_0$$

3-phase converter losses



One half-bridge of a three-phase voltage source converter.



Converter output voltage and current. The current is displaced by an angle φ relative to the voltage.

Loss estimation

Switching losses:

$$\overline{P}_{Ti,sw}=\frac{1}{T_n}\int_{T_n}\left(P_{on}+P_{off}\right)dt=\frac{f_{sw}}{T_n}\int_{T_n}\left(E_{on}+E_{off}\right)dt=\frac{E_{on,n}+E_{off,n}}{V_{dc,n}\cdot I_n}\cdot\frac{V_{dc}f_{sw}}{T_n}\int_{T_n}\left|\hat{i}_i\sin(\omega_1 t-\varphi)\right|dt=\frac{2\sqrt{2}}{\pi}\cdot\frac{E_{on,n}+E_{off,n}}{V_{dc,n}\cdot I_n}\cdot V_{dc}I_i f_{sw}$$

$$\overline{P}_{Di,sw}=\frac{1}{T_n}\int_{T_n}\left(P_{on}+P_{off}\right)dt=\frac{f_{sw}}{T_n}\int_{T_n}\left(E_{on}+E_{off}\right)dt=\frac{2\sqrt{2}}{\pi}\cdot\frac{E_{off,n}}{V_{dc,n}\cdot I_n}\cdot V_{dc}I_i f_{sw}=\frac{2\sqrt{2}}{\pi}\cdot\frac{E_{Drr,n}}{V_{dc,n}\cdot I_n}\cdot V_{dc}I_i f_{sw}$$

Conduction losses:

$$\overline{P}_{Ti,cond}=\left(\frac{\sqrt{2}}{\pi}\cdot V_{T0}I_i+\frac{1}{2}\cdot R_{T(on)}I_i^2\right)+\left(V_{T0}I_i+\frac{4\sqrt{2}}{3\pi}\cdot R_{T(on)}I_i^2\right)\cdot\frac{U_i\cos(\varphi)}{V_{dc}}$$

$$\overline{P}_{Di,cond}=\left(\frac{\sqrt{2}}{\pi}\cdot V_{D0}I_i+\frac{1}{2}\cdot R_{D(on)}I_i^2\right)-\left(V_{D0}I_i+\frac{4\sqrt{2}}{3\pi}\cdot R_{D(on)}I_i^2\right)\cdot\frac{U_i\cos(\varphi)}{V_{dc}}$$

Example :

V_to = 0.95; % [V]
V_do = 1.65; % [V]
R_t_on = 0.5/300;   % [Ohm]
R_d_on = 0; % [Ohm]
E_d_rr = 0.0485; % [J]
E_on = 26e-3; % [J]
E_off = 55.5e-3; % [J]

V_dc_n = 600; % [V]
I_n = 450; % [A]

Udc = 600; % [V]
P_max = 200000; % [W]


Technische Information / Technical Information

IGBT-Module
IGBT-modules

FF450R12ME4

EconoDUAL™3 Modul mit Trench/Feldstopp IGBT4 und Emitter Controlled HE Diode und NTC
EconoDUAL™3 module with Trench/Fieldstop IGBT4 and Emitter Controlled HE diode and NTC

V_{CES} = 1200V
$I_{C\,nom}$ = 450A / I_{CRM} = 900A

Typische Anwendungen
- Motorantriebe
- Servoumrichter
- USV-Systeme
- Windgeneratoren

Typical Applications
- Motor Drives
- Servo Drives
- UPS Systems
- Wind Turbines

Elektrische Eigenschaften
- Niedriges V_{CEsat}
- $T_{vj\,op}$ = 150°C

Electrical Features
- Low V_{CEsat}
- $T_{vj\,op}$ = 150°C

Mechanische Eigenschaften
- Standardgehäuse

Mechanical Features
- Standard Housing

Module Label Code
Barcode Code 128

DMX - Code

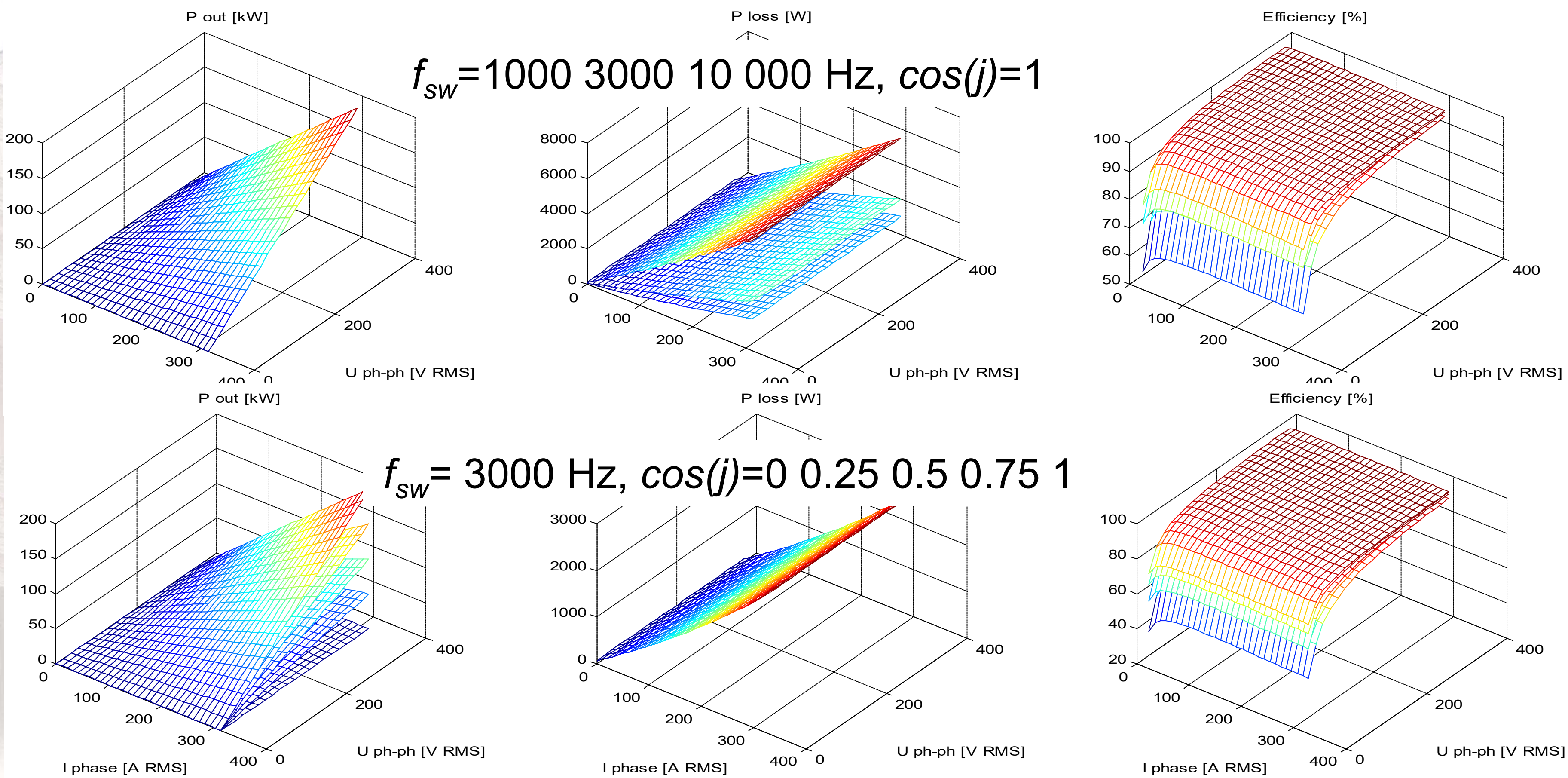
Content of the Code	Digit
Module Serial Number	1 - 5
Module Material Number	6 - 11
Production Order Number	12 - 19
Datecode (Production Year)	20 - 21
Datecode (Production Week)	22 - 23

prepared by: CU
approved by: MK
date of publication: 2013-11-04
revision: 3.1
UL approved (E83335)
1

Converter Efficiency for different f_{sw} & $cos(\varphi)$

f_{sw}=1000 3000 10 000 Hz, *cos(j)*=1

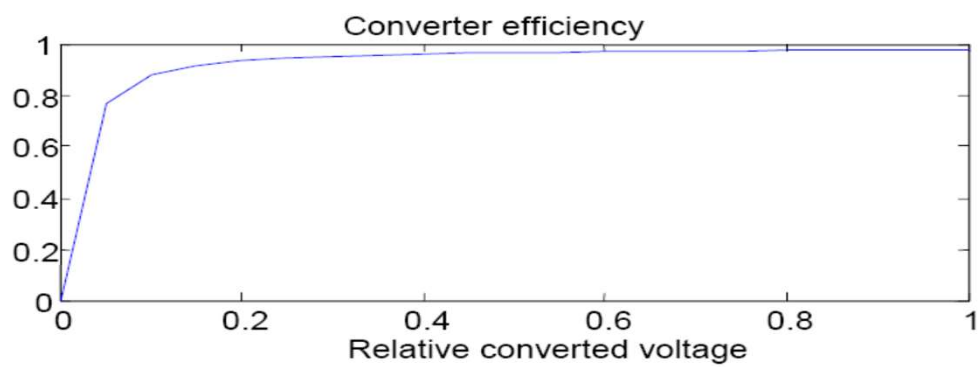
f_{sw}= 3000 Hz, *cos(j)*=0 0.25 0.5 0.75 1



Power Electronic Efficiency

- Mostly depending on the ratio

$$\frac{\text{Output voltage}}{\text{DC link voltage}}$$



- Almost constant over wide operating range
- Can be represented by a constant, e.g. 0.97